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Auditory Perception in an Open Space: Detection and Recognition

by Kim F Fluitt, Timothy J Mermagen, Szymon Letowski, and Tomasz Letowski

ARL-TR-7305 **June 2015**

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
June 2015	Final	July 2001–August 2001

4. TITLE AND SUBTITLE
Auditory Perception in an Open Space: Detection and Recognition

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Kim F Fluitt, Timothy J Mermagen, Szymon Letowski, and Tomasz Letowski

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army Research Laboratory
ATTN: RDRL-HRS-D
Aberdeen Proving Ground, MD 21005-5425

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-7305

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The purpose of the current study was to investigate the effects of distance and meteorological conditions on detection and recognition of, and distance estimation to, various sound sources spread across a large open field. This report presents results of the detection and recognition tasks. Both acoustic (target sound and noise level) and meteorological (wind direction and strength, temperature, atmospheric pressure, humidity) data were collected for each experimental trial. Twenty-four subjects participated in this study. Eight various sounds delivered from 6 test loudspeakers were presented to the listeners. The results indicate that in most cases as soon as a sound is detected, it is recognized. In most cases both the detection and recognition of sound sources declined rapidly at distances greater than approximately 100–200 m. The main effects of weather conditions and environmental noise are strongly correlated. Some expectations of sound propagation were not observed during data collection; specifically, sounds were more easily heard in the afternoon as opposed to the morning, which meant that participants detected and recognized sounds more accurately in the afternoon than in the morning. This was most likely attributed to the varying effects of temperature, humidity, and background noise in relatively very hot listening conditions. However, the overall performance of participants was very close to the results predicted by in-house software that modeled human detection of sounds.

15. SUBJECT TERMS
auditory distance estimation, detection, recognition, sound propagation

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER (*Include area code*)
Unclassified	Unclassified	Unclassified	UU	66	Kim F Fluitt / 410-278-5850

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. Introduction

Most human activities rely on the sense of vision, especially military activities. However, vision can be limited in tactical situations and is often obscured by terrain, buildings, fog, and vegetation. Most importantly, half of the day is night (Hodge and Mazurczak 1975). In all such low-visibility cases, hearing becomes the primary long-distance sense guiding human actions and decisions. Even during good visibility, sound is an important source of information. Sound waves, unlike light waves, bend around obstacles and reveal hidden sound-emitting objects. Furthermore, hearing is a 360° sense, again unlike binocular vision, that can extend a little beyond a 120° angle (Karmarkar 2014). In addition, objects that look alike may be differentiated by their acoustic signatures (e.g., empty versus a full truck).

Accurate sound perception is directly related to both Soldier mission and safety (Katzell et al. 1952; Abouchacra et al. 2007). Infantry Soldiers generally agree that in limited-visibility environments, the sense of hearing is their main survival resource. In combat, detected sounds alert the Soldier that "something is there", and early recognition of the sound source allows the Soldier to take swift action (Price and Hodge 1976a, 1976b). The farther away the sound source is detected and recognized, the longer time the Soldier has to respond to the threat (Abouchacra et al. 2007). Therefore, early detection, localization, and recognition of surrounding sound sources are critical in any military operation.

The effectiveness of hearing, as well as other long-distance senses such as vision and smell, depends on the person, surrounding environment, and the interaction between the two. Auditory detection and recognition of acoustic sources in an open field are affected by a large number of technical, physiologic, psychological, and environmental conditions, such as the type of sound, the distance to a sound source, terrain configuration, proximity of reflective surfaces (buildings, bodies of water, tree lines), meteorological conditions (wind, temperature, precipitation, humidity), hearing capabilities of the listener, the level of background noise, whether or not the listener is wearing protective gear (helmet or ear plugs), and the listener's familiarity with the sound source. Such large sets of variables that affect signal detection and recognition make it difficult to predict whether the enemy can hear a given acoustic signature or if the Soldiers on the ground can differentiate, for example, the sounds of various helicopters flying just above the tree line. However, such predictions are necessary in almost all areas of military activities as well as in civilian applications (e.g., audibility of warning signals, rescue missions, large stadium designs). In all these cases it is important to know when a certain sound can or cannot be heard and whether or not it may be identified. To understand the whole complexity of factors affecting auditory performance, some relatively simple listening situations need to be considered prior to more complex and variable conditions.

The primary purpose of this reported study was to determine audibility and recognizability of selected acoustic signals emitted from various distances in a wide open field under relatively neutral environmental conditions. The results of the study are intended to be used to better our understanding of conditions and processes affecting perception of sounds propagating outdoors. The secondary goal of the study is to provide a realistic data set that can be used for developing and verifying various auditory models that predict audibility of sounds under various military and civilian operational conditions.

2. Sound Propagation in an Open Space

Sound detection and recognition depend on the sound source, factors affecting sound propagation through the space, and the listener. The signal emitted by a sound source can be generally characterized by its level, dynamic range, signal-to-noise ratio, duration, temporal variability, and bandwidth. The listener-related factors include biological factors, such as hearing acuity and memory, and behavioral factors, such as response proclivity, experience, attention, familiarity with signal and environment, stress, and expectations. In particular, detectability of a signal may depend on expected informational content (utility) of the stimulus, expected reward, listener's habituation, and the listener's current needs.

The factors affecting sound propagation through space are dependent on the type of environment (or space), and the type and behavior of the propagating medium filling the space. In an unbounded free-field space, the sound intensity declines with the rate of 6 dB per doubling of the distance from the sound source because of spherical spreading (divergence) of sound energy in space. In such an ideal space, sound energy arriving at the listener would be exactly known if the sound energy emitted by the sound source and the distance to the listener are known. In a real outdoor environment the spherical spreading of sound energy is affected by the presence of the ground surface and may be limited to a hemisphere or a certain geometrical angle smaller than a spherical (360°) angle. Hence, such spreading is generally called the geometrical spreading. In addition, sound propagation through the outdoor environment is affected by terrain topography, ground type and its cover, and several environmental factors, including locations of both the sound source and the listener in respect to the ground, absorption of sound by air, weather conditions, time of day, and locations of various reflecting objects in the space (barriers, buildings, lines of trees, etc.). The main elements of the outdoor environment affecting propagation of sound and their main variables are listed in Table 1.

Table 1 Main factors contributing to attenuation of acoustic signals propagating in the outdoor environment (adapted from Fidell and Bishop [1974])

Environmental Factor	**Major Variables**
Geometric spreading	Spherical angle, distance
Atmospheric absorption	Temperature, relative humidity, atmospheric pressure, distance
Temperature and wind gradients	Temperature, wind velocity, and direction
Ground reflections	Source height, receiver height, ground impedance
Ground absorption	Ground impedance
Obstacles and acoustic shadow	Geometric relationships

Geometric spreading is the main source of decreasing sound level with increasing distance from the sound source. This is the basic source of sound attenuation in an open space. All other factors listed in Table 1 cause so-called excess attenuation, which is the attenuation caused by the environment. Excess attenuation generally increases with the frequency of the propagating signal and in some cases can be quite substantial. Therefore, for discussion of a person's ability to detect and recognize sounds in the open space, some review of the main factors affecting sound propagation in the open space may be helpful.

2.1 Geometric Spreading

When an ideal point source (acoustic monopole) radiates sound energy in an unbounded sound field (free field), sound energy spreads in all directions (wave-front spreading), and the sound intensity ($\boldsymbol{I}$) at a given point in space is a function of distance ($\boldsymbol{r}$) from the sound source

$$I = \frac{W}{4\pi r^2}, \tag{1}$$

where W is the power of the sound source (watts). Equation 1 is commonly referred to as the inverse-square law. This law applies only to the ideal omnidirectional sound source operating in unlimited space and in the ideal medium, which does not attenuate sound energy. Based on Eq. 1, the sound intensity level ($\boldsymbol{i}$) radiated by the sound source decreases at the rate of 6 dB for every doubling of the distance[1] from the point-like sound source (e.g., weapon fire, flying bullet, or an alarm) to the observer (listener) according to the formula

$$\Delta i = 10log\frac{I_2}{I_1} = 20log\frac{r_2}{r_1}, \tag{2}$$

where $\boldsymbol{\Delta i}$ is the difference in the sound intensity level between the sound source location and the observation point, and $\boldsymbol{I_1}$ and $\boldsymbol{I_2}$ are the sound intensities at the sound source and at the observation point, respectively. Please note that the 6-dB rate of sound decay means that sound intensity decreases 4 times, and sound pressure decreases twice per doubling of the distance. In calculating sound intensity level (dB IL) and sound pressure level (dB SPL) existing at a specific point in space, the common reference values are $\boldsymbol{I_o} = 10^{-12}$ W/m^2 and $\boldsymbol{p_o} = 20 \times 10^{-6}$ Pa, respectively. The 6-dB decay per doubling of the distance only applies to free-field sound or anechoic conditions.

In a case of the outdoor space and the sound source located close to the ground, spherical spreading becomes hemispherical spreading or a spreading limited to a certain geometrical angle. Typical sound decay outdoors over soft ground is about 4.5 dB per doubling the distance. In reverberant environments the decrease is even less (e.g., 4.25 dB in a normal room) because of sound reflections from space boundaries (Zahorik and Wightman 2001).

Assuming that sound intensity at the sound source location is always measured at the distance $\boldsymbol{r_1}$ = 1 m, Eq. 2 can be reduced to

$$\Delta i = 20\log(r_2). \tag{3}$$

Equations 2 and 3 are valid for an ideal point sound source operating in a free sound field but fail in the case of real sound sources, which, unlike the ideal point source, have finite dimensions and, at close range, cannot be treated as a point source. The sound waves produced by various parts of a real sound source interact in the space close to the source's surface. The interaction, which consists of constructive and destructive interference of multiple waves originating from various locations on the sound source's surface, creates a complex pattern of spatial maxima and minima of sound intensity. As a result, close to the sound source's surface the sound intensity does not obey the inverse-square law, and the particle velocity is not in phase with sound pressure. However, at some greater distance from the surface, these separate pressure waves combine to form a relatively uniform front that propagates away from the source.

The distance from the sound source where the pattern of spatially distributed maxima and minima merges in a uniform waveform front is approximately equal to the wavelength (λ) of the radiated sound (Morse and Ingård 1968). The distant sound field, where the sound source can be treated as a point source and the sound wave can be treated as a plane wave, is called the far field. The area near the sound source where these conditions are not met is called the near field. The notional border line separating near and far sound fields is a function of sound frequency and is shown in Fig. 1.

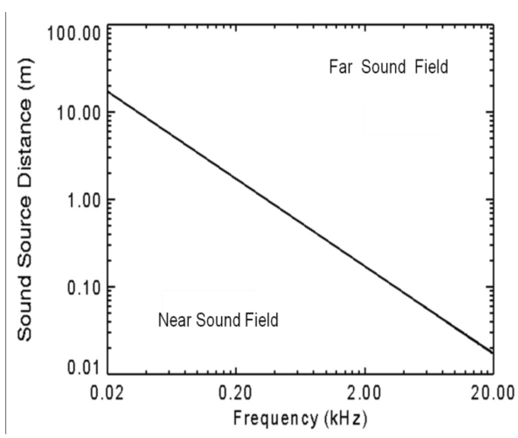


Fig. 1 The hypothetical border between near and far sound fields of the sound source propagating in air as a function of sound frequency (adapted from Morse and Ingård 1968)

In regard to sound sources radiating energy in an open field, most real sound sources are not omnidirectional and radiate most of their energy in certain specific directions. Such sound sources are directional and can be described as dipole, quadrupole, etc. The directionality of the sound source is captured by its directivity factor $\boldsymbol{Q}$, and it needs to be taken into account in calculating the sound intensity existing at a given distance and direction. Factor $\boldsymbol{Q}$ depends on sound frequency and is equal to one ($\boldsymbol{Q}$ = 1) when the sound source is effectively omnidirectional. Sound sources tend to be omnidirectional at low frequencies when the wavelength of a sound wave is large in comparison to the dimensions of the sound source. Factor $\boldsymbol{Q}$ can be as large as 10 or more for very directional sound sources. To account for sound source directivity, Eq. 1 can be modified as

$$I = \frac{QW}{4\pi r^2}. \tag{4}$$

This equation is valid for only the observation point that is located on the main radiation axis of the sound source. The logarithmic form of the factor $\boldsymbol{Q}$,

$$DI = 10logQ, \tag{5}$$

is called directivity index (DI) and is expressed in decibels. For an omnidirectional sound source radiating into unlimited free space, DI = 0. For the same sound source radiating energy close to an ideal reflective surface (hemispherical radiation), DI = 3 dB (Lamancusa 2000).

2.2 Atmospheric Absorption

In a real medium, such as air, sound energy propagating through the medium not only spreads in different directions but is also absorbed by the medium, resulting in the exponential decay of energy described as the inverse exponential power law known as the Beer-Lambert law. According to this law

$$I = I_o e^{-\alpha d}, \tag{6}$$

where I_o and I are sound intensities at the sound source and the observation point, respectively, d is the distance between these 2 points, and α is the absorption coefficient of the medium. Absorption of sound energy by a medium, called atmospheric absorption, is the result of internal friction within the medium that converts acoustic energy into heat. The basic mechanisms of atmospheric absorption are heat conduction, shear viscosity, and molecular relaxation processes (Sutherland and Daigle 1997). The amount of energy loss caused by these mechanisms depends on sound frequency, temperature and atmospheric (static) pressure within the medium, and in the case of molecular relaxation processes, on humidity of the medium (air). This means that changes in meteorological conditions (weather) have a large effect on sound propagation. Note, however, that light rain and fog have relatively very small effects on sound propagation. For example, heavy natural fog attenuates sound in the order of 1.5 dB/km (Ungar 1972, p. 176).

The relationship between the amount of sound energy absorbed at given frequencies by a medium and meteorological conditions (temperature, atmospheric pressure, and humidity) are complex non-monotonic functions in which the actual amount of absorption needs to be calculated for specific combinations of these conditions. For example, sound absorption at 30 °C is greater for relative humidity of 10% than for 40%, while the reverse is true for 15 °C (e.g., Harris 1966). Combining Eqs. 4 and 6, one can predict sound intensity in a real medium as

$$I = \frac{QW}{4\pi r^2} e^{-\alpha d} \,. \tag{7}$$

At intermediate distances, up to approximately 200 m (Albert 2004), and at low frequencies the loss of sound energy due to atmospheric absorption by a laminar (not turbulent) medium is usually small and can be negligible. However, at large distances and high frequencies, energy loss due to atmospheric absorption can be quite large and exceed the loss caused by a 3-dimensional spread of energy. The effect of atmospheric absorption on sounds with high-frequency energy above 10 kHz "can become distinctly audible at distances as short as 15 m" (Blauert 2001).

The relationship between the coefficient of absorption (α), sound frequency, temperature, atmospheric pressure, and relative humidity of the propagating medium can be calculated as

$$\alpha = 8.686 f^2 \sqrt{\tau} \times \left[\frac{1.84\times10^{-11}}{\rho} + \frac{(b_1+b_2)}{\tau^3}\right] , \tag{8}$$

where f is sound frequency in hertz, τ is relative temperature ($\tau = T/T_{20}$ in degrees kelvin; T_{20} = 293.15 degrees kelvin), ρ is relative atmospheric pressure ($\rho = p/p_n$ in pascals; p_n = 101,325 Pa), r_h is relative humidity in percent, and b_1 and b_2 are complex coefficients dependent on relative humidity r_h in percent, relative temperature τ, sound frequency f, and relaxation frequencies f_n and f_o of nitrogen and oxygen (see ISO 9613-1 [1993], Sutherland and Daigle [1997], or Salomons [2001] for a more detailed description of b_1 and b_2 coefficients, which are functions of some of the variables listed above). According to this formula, the coefficient of absorption is proportional to the square of the frequency and is a complex function of weather conditions. The formula is valid for pure tones and narrow-band noises. Its accuracy is estimated to be ±10% for $153 < T < 323$ K, $0.05 < h$ (concentration of water in the atmosphere; $h = r_h (p/p_n)$) < 5%, $p <$ 200,000 Pa, and $0.0004 < f/p < 10$ Hz/Pa (Salomons 2001, p. 111). An example of the dependence of the absorption coefficient on frequency for a specific set of environmental conditions is shown in Table 2. Note, however, that Eq. 8 does not take into account the presence of wind and properties of the ground's surface.

Table 2 Atmospheric absorption coefficient α (in decibels per kilometer) for the preferred one-third-octave center frequencies f_c (in hertz) (T = 283.15 K [10 °C]; r_h = 80%; p = 101,325 Pa [1 atm])

f_c	25	50	100	200	400	800	1600	3150	6300
	31.5	63	125	250	500	1000	2000	4000	8000
	40	80	160	315	630	1250	2500	5000	10000
α	0.018	0.07	0.25	0.77	1.63	2.88	6.3	18.8	67.0
	0.028	0.11	0.37	1.02	1.96	3.57	8.8	29.0	105.0
	0.045	0.17	0.55	1.31	2.36	4.58	12.6	43.7	157.0

Garinther and Moreland (1966) wrote that approximate atmospheric absorption at 200-m distance ranges from 0 dB at low auditory frequencies to about 10 dB at high auditory frequencies. The step-by-step procedures for calculating atmospheric losses can be found in an American National Standards Institute (ANSI) (1995) standard and as an applet on the Web (http://www.sengpielaudio.com/calculator-air.htm).

2.3 Ground Effect

Geometrical spread of sound energy and atmospheric absorption are 2 main sources of attenuation of energy of the propagating sound. However, there are also several others. Sound waves propagating close to the ground surface are absorbed and reflected by the ground. This additional factor affecting sound propagation is called the ground effect or ground attenuation. Constructive interactions between direct and reflected sound waves may increase the sound level at the listener by up to 6 dB. Destructive interaction may, in the worst case, completely cancel out the sound. In general, the softer the ground, the greater the ground attenuation.

The overall amount of ground attenuation depends on the type of ground (ground impedance), sound frequency, distance "over the ground" between the sound source and the listener, and the heights of both the sound source and the listener above the ground surface. In the case of a grassy field, the ground absorption is most pronounced in the 200- to 600-Hz range, where it can decrease the sound level by as much as 25 dB (Garinther and Thompson 1993) and extends toward higher frequencies with increasing distance between the sound source and the listener (Sutherland and Daigle 1997; Lamancusa 2000). Essentially, greater distances between the sound source and the listener result in greater attenuations in wider frequency ranges due to the ground effect (Piercy et al. 1977; Embleton 1996). The closer the sound source is located to the surface of the ground, the greater the amount of ground attenuation and the greater the attenuation of energy at high frequencies. The same applies to the height of the listener's ears above the ground level. For example, for a listener's ear located 1.2 m above the ground level and at a distance of 300 m from the sound source, the excess sound attenuation caused by the ground effect decreases from 20 to 9 dB as the sound source height increases from 0.12 to 12 m (Garinther et al. 1985). The presence of wind and changes in air temperature with level above the ground surface are additional factors affecting sound propagation.

2.4 Wind and Other Open Space Effects

When sound travels through still air with uniform atmospheric conditions, it propagates in straight lines. However, changes in wind conditions (velocity and direction), as well as temperature, with altitude (height above the ground) affect sound velocity and cause sound waves to propagate along curved lines. This effect is called atmospheric refraction.[2] Wind also creates noise by moving vegetation and causing nonlinear effects passing over obstacles. Such noise is called wind noise. The wind noise has approximately a 1/f spectrum with the highest noise levels occurring below 100 Hz.

Under normal sunny conditions, solar radiation heats the Earth's surface, and at low altitudes the atmosphere is warmer, causing a temperature gradient and the sound velocity to be higher in the warmer air. In the evening, the Earth's surface cools down, and the temperature gradient reverses itself. These 2 respective temperature conditions are called temperature lapse and temperature inversion. Similarly, wind conditions depend on the height above the ground because of the slowing of the wind velocity at the ground surface due to surface friction. This causes a wind gradient, which is analogous to a temperature gradient. When sound velocity decreases with height (daytime sunny warming of the ground), it causes an upward bend of the sound wave (upward refraction) and creates refractive shadow zones with poor audibility of the propagating sound. Conversely, when sound velocity increases with height (evening temperature conversion chilling the ground), it causes a downward bend of sound waves (downward refraction), leading to multiple reflections at the ground surface and resulting in good audibility of the sound over a long range (Heimann 2003). Downward refraction explains why sound sources can be heard at larger than normal distances. This, together with the reduced level of man-made noise at night, explains why sounds are typically heard at much larger distances at night than during the day.

Upward or downward refraction of sound caused by the wind can decrease or increase the expected sound level at the listener location compared to a no-wind condition by as much as ±10 dB (e.g., Ingård 1953). For example, Garinther and Moreland (1966) observed that in a downwind sound propagation (wind blowing from the sound source to the listener), sound attenuation is frequency dependent and for a moderate wind velocity is equal to only about 2 dB for a 1000-Hz tone and 10 dB for a 5000-Hz tone at 200-m distance. For an upwind situation (wind blowing against the propagating sound), the excess attenuation of sound is practically frequency independent and negligible up to about 60 m while increasing to about 27 dB at 170 m. This attenuation is not only the effect of wind velocity but also the result of a deformation of the wave front. Wiener and Keast (1959) give idealized attenuation functions for downwind and upwind propagation over open terrain ground, as shown in Fig. 2. Wiener and Keast (1959) do not give an explanation for the excess downwind sound attenuation at longer distances.

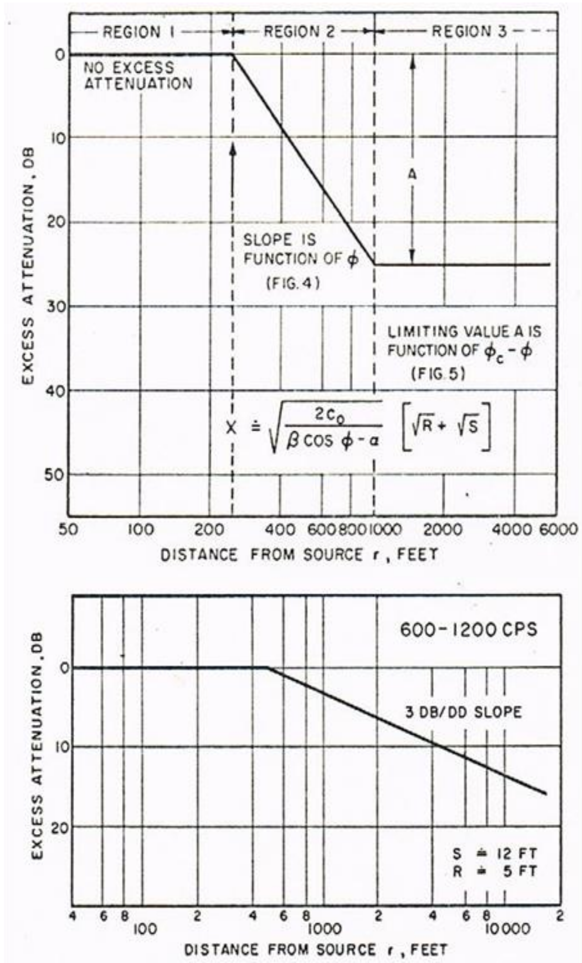


Fig. 2 Idealized functions of changes in sound pressure level (decibel sound pressure level) due to upwind (upper panel) and downwind (bottom panel) sound propagation over open ground as a function of the distance from a sound source. Illustrated attenuation is additional to attenuation caused by sound divergence and atmospheric attenuation. (Reproduced with permission from Wiener FM, Keast DN. Experimental study of the propagation of sound over ground. Journal of the Acoustical Society of America. 1959;31(6):725–733. Copyright 1959, Acoustical Society of America. http://dx.doi.org/10.1121/1.1907778)

Under normal sunny conditions wind direction and velocity do not change much over short periods of time. However, even small changes in temperature and humidity can cause large changes in wind behavior.[3] Atmospheric turbulence, i.e., the existence of regions of inhomogeneity in air velocity caused by local variations in temperature and wind velocity, also affects sound propagation by scattering sound energy. The changes in sound level caused by atmospheric turbulence are time dependent and are characterized by an increased sound level in acoustic shadow zones. The magnitude of these fluctuations is larger close to the ground than

higher in the atmosphere since fluctuations in both direct sound waves and sound waves reflected from the ground can cause relatively large variations in the interference pattern. However, the scattering effect is only large at high frequencies and can be neglected at low frequencies (e.g., Scholes 1968). For example, Delaney (1969) reported that attenuation of sound due to scattering is of the order of 1 dB/km for a 500-Hz sound.

All solid objects, such as berms, barriers, and towers, that are in the path of the propagating sound also disrupt the natural propagation of sound energy causing diffraction and reflection of sound energy. The depth of the acoustic shadow zones created behind these objects depends on geometry of the object, sound frequency, and direction of the wind. A barrier with a height that reaches up to a line of sight provides attenuation of about 5 dB or more across most of the auditory frequency range, and higher barriers can attenuate sound by as much as 25 dB (Garinther and Thompson 1993). Heimann (2003) reported 5-dB attenuation of a 100-Hz tone by a 50-m-wide dense stand of 20-m-high trees, and Heisler et al. (1987) reported an 8 dB A-weighted attenuation of highway noise by 100 m of red pine forest growing next to the highway.

Sound attenuation caused by forests is usually negligible at low frequencies and should only be taken into account at frequencies higher than 500–1000 Hz (Moreland et al. 1965; Bullen and Fricke 1982). According to Aylor (1972) and United Facility Criteria (UFC, 2003), sound attenuation caused by medium-dense woods is 9 dB per 100-m distance at 1000 Hz and 15 dB per 100 m at 4000 Hz. Wiens et al. (2008) measured sound attenuation in New Zealand forest and reported 0.528 dB/m in the 800- to 2200-Hz frequency range. They also reported that reverberation time (RT) of the forest environment varied from 0.08 to 2.8 s at distances from 30 to 75 m from the sound source. According to Bullen and Fricke (1982) sound attenuation caused by dense forest made of large trees (e.g., jungle) can be estimated for frequencies above 2000 Hz as

$$\Delta I\ d = 8.5 + 0.12D, \tag{9}$$

where D is the depth of an infinitely wide belt of forest[4] (in meters). Referring to some unspecified data, Garinther and Moreland (1966, p.11) noted that “for dense evergreen woods, the excess attenuation varies nearly linearly from about 5 dB to 45 dB per 30 m for frequencies of about 40 Hz to 3500 Hz.”

Foliage lying on the ground (but not walked through) provides minimal sound attenuation. One hundred meters or more of dense hardwood brush foliage was found to only minimally attenuate low-frequency sounds (2 dB at 500 Hz and 5 dB at 4000 Hz) with attenuation reaching 10–20 dB at frequencies above 4000 Hz (Garinther et al. 1985; Garinther and Thompson 1993). However, a thick layer of fallen leaves laying on a hard surface may sometimes have an effect on low frequencies because it reduces the ground flow resistance (Neiswander 1983). For a jungle environment, Embleton (1963) and Dobbins and Kindick (1966) reported that at short propagation distances of up to about 60 m (200 ft) sound attenuation was directly proportional to sound frequency. It changed linearly per doubling the distance up to 60 m (200 ft) and increased exponentially at farther distances.

3. Environmental Noise Levels

Another first-order factor affecting audibility of acoustic signals in an open space are the properties (level and spectral characteristics) of background noise. These properties can vary widely depending on the type of environment (e.g., rural, industrial, highway, urban), time of the day (e.g., day, night), and weather conditions (e.g., presence of wind). In general, the level of background noise is dependent on the distance from places characterized by intense human activities (cities, highways, factories, construction sites) as well as noisy natural landmarks (e.g., waterfalls). The one-third-octave spectral properties of background noises recorded in several quiet environmental areas that are relatively free from human interference are shown in Table 3.

Table 3 Typical (average) one-third-octave spectra of environmental noises recorded at several natural locations

Octave Frequency (Hz)	Sound Level (dB SPL)									
	North Rim Grand Canyon[a]	Tropic Forest (Panama) Day[b]	Tropic Forest (Panama) Night[b]	Rural Forest (Germany) Day[c]	Rural Farm[a] (Min Values)	Rural Farm[a] (Mean Values)	Rural Farm[a] (Max Values)	Surf at Wallops Island (VA)[d]	Tropic Forest[e] (No Insects and Animals)	Tropic Forest[e] (with Insects and Animals)
50	18	32	34	28	34	38	43	. . .	. . .	. . .
63	17	29	32	26	37	40	46	. . .		
80	16	27	30	25	38	43	48	60		
100	15	25	28	23	38	42	46	60	23	23
125	14	23	26	21	37	40	45	59		
160	13	23	23	19	34	38	42	55		
200	12	23	21	18	31	36	41	53	24	24
250	11	23	20	16	28	34	40	51		
315	10	22	19	15	26	33	39	50		
400	9	21	19	14	25	32	37	49	23	24
500	8	20	19	13	24	30	36	49		
630	6	20	20	12	24	29	34	49		
800	5	20	21	10	23	28	34	49	18	22
1000	5	20	22	9	22	27	33	49		
1250	5	20	22	9	21	26	32	49		
1600	4	20	22	8	19	24	30	47	19	30
2000	4	20	22	7	18	23	28	46		
2500	3	19	23	7	16	21	26	43		
3150	2	18	24	6	15	20	23	42	24	45
4000	1	17	27	6	14	18	22	40		
5000	0	17	29	6	12	16	20	37		
6300	0	17	33	7	10	14	19	. . .	26	50
8000	–1	17	37	7	9	13	17	. . .		
10000	–1	18	42	8	8	12	16	. . .		

Notes: The spectra are based on the data published by Abrahamson[d] (1974), Dobbins and Kindick[b] (1966), EPA[a] (1971), Remington and Biker[c] (1982), and Eyring[e] (1945). The one-third-octave levels for Dobbins and Kindick's (1966) and Remington and Biker's (1982) data have been computed from the original octave band data by Garinther et al. (1985). Eyring's (1945) data have been converted to octave band levels from the original data by Garinther (1995 personal communication).

Typical variation in community noise during daytime is about 30 dB (EPA 1971, 1974). Average background noise levels at night at remote rural environments are typically somewhat higher (~3 dB) than during daytime because of nocturnal activities of various insects, birds, and other animals. Conversely, nighttime background noise levels close to human communities are about 10 dB lower than daytime levels because of a decrease in human activities at night. Refraction effects due to wind and temperature gradients that occur during the daytime (wind velocities tend to be lower at night) can produce shadow zones that may significantly decrease detectability of sound sources in comparison to evening, night, and early morning environmental conditions. At night, temperature is lower near the ground and sound waves tend to be bent toward the ground, increasing relative audibility of sound sources by up to 3 dB (Garinther et al. 1985).

In general, all biological processes have long-term frequency spectra that are described by the $1/f^{\delta}$ function, where δ depends on the type of process and environment (Steele 1985; Vasseur and Yodzis 2004). Inland environmental noises are characterized by relatively uniform spectra ($\delta \sim 0$–1.0) (see Table 3) while marine noises are characterized by spectra with $\delta \sim 1.5$–2. The data presented in Table 3, as well as in other reports (e.g., De Coensel et al. 2003; Gjestland 2008; Miller 2008), indicate that noises in rural grassland or woodland areas with no wind are characterized by 1/f spectra with peaks caused by the presence of various organisms in the area, e.g., amphibians (1–2 kHz), birds (4–5 kHz), and insects (6–7 kHz) (Napoletano 2004).

The presence of wind causes an increase in noise level, mostly due to the increase in vegetation noise at low frequencies (De Coensel et al. 2003). Examples of the relationship between wind velocity and resulting noise level are shown in Fig. 3. In general, the level of wind-generated noise in vegetation is proportional to the logarithm of wind velocity.

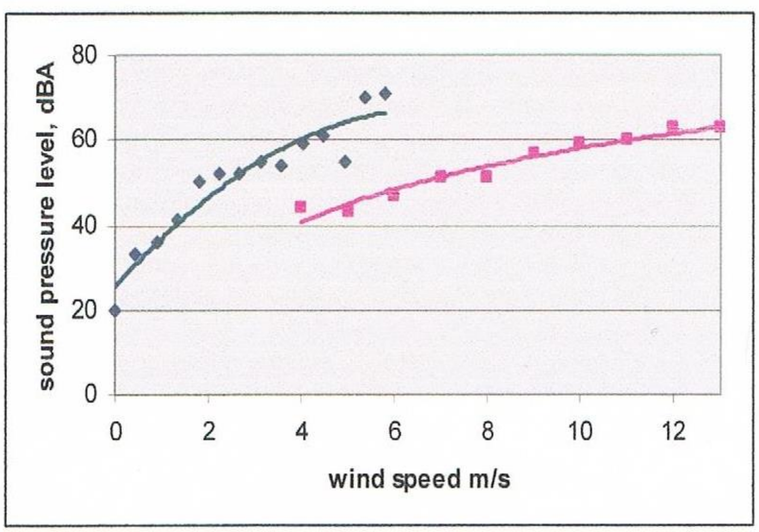


Fig. 3 Noise generated in foliage by passing wind. The two curves correspond to different types of vegetation: woodland (blue) and (grassland) red (adapted from Gjestland 2008).

Human-made noises, such as construction, highway, and urban noises, also have frequency spectra with 1/f envelopes at higher frequencies. These spectra have a tendency to “flatten out” or even drop to some degree at very low frequencies (<100 Hz) (e.g., Bonvallet 1951; Cornillon and Keane 1977; Skånberg and Öhrström 2006). Just as the spectra from rural areas, these spectra may have some additional frequency maxima resulting from specific dominating noise sources. For example, the spectrum of tire noise (over a paved surface) is broadly distributed with a maximum around 1 kHz. In addition, at larger distances from specific human-made sound sources, the spectra usually have a certain mid-frequency dip (300–600 Hz) due to ground absorption.

4. Auditory Perception in an Open Field

Auditory perception is the collection, identification, organization, and interpretation of acoustic information arriving at the listener’s ears, and it supports the listener’s understanding and cognitive representation of the environment. It can result in an awareness of the presence, behavior, and meaning of a variety of sound sources operating in the surrounding environment. The degree of sensitivity of a person to a specific sound source can depend on how the person’s well-being and survival are influenced by a sound source. In other words, people are the most sensitive to sounds that potentially affect their state of being, either positively or negatively (Casey 1998, p. 24).

Depending on the level of complexity of the auditory task performed by a person, it may involve detection, discrimination, classification, recognition, identification, comprehension, directional localization of, and auditory distance estimation to one or more sound sources. The basic definitions of these tasks are given in Table 4.

Table 4 Basic definition of the auditory perceptual tasks

Auditory Task	**Definition**
Detection	Determination of the presence of an acoustic signal
Discrimination	Differentiation of one acoustic signal from another
Classification	Division of acoustic signals into groups according to their type
Categorization	Assigning an acoustic signal to a broad class of signals
Recognition	Determination of the source of the acoustic signal or the narrow class of sounds it belongs to
Identification	Determination of the source of the sound signal exactly
Comprehension	Understanding the meaning of the acoustic signal
Localization	Determination of the location of the sound source
Directional Localization	Determination of the direction toward the sound source
Distance Estimation	Determination of the distance to the sound source

In listening to sounds, Gaver (1993) makes an important distinction between 2 types of listening: musical listening and everyday listening. Musical listening is listening to the attributes of sound such as timbre, loudness, duration, or pitch. Everyday listening is listening to the properties of the event that causes the sound. In terms of the everyday listening we hear a *person*, who is *walking* toward us *through fallen leaves*. The phenomenological distinction between musical and everyday listening explains, for example, the parallel existence of 2 definitions of timbre as the property that differentiates 2 sounds having the same loudness and pitch (musical listening) and as the property that allows identification of the sound source (everyday listening). It is important to note that the complexity of the sound has nothing to do with the complexity of the analysis the listener has to do while performing an everyday listening task. Actually, and quite paradoxically, the more complex the sound, the fewer confusions it creates and the easier it is to perceive (Casey 1998).

The 2 perceptual tasks of detection and recognition further discussed in this report are everyday listening tasks. In these tasks, the listener is to perform both detection and recognition of remote sound sources operating at various distances in an open outdoor environment.

4.1 Detection

Auditory detection is the attainment of an "awareness" that an acoustic signal is present. Human ability to detect sound is a combination of a person's hearing sensitivity and listening proficiency (listening skills). Hearing sensitivity is usually defined by the concept of the absolute threshold of hearing. For sound to be detected its level must be above the listener's threshold of hearing in a spectro-temporal space. Listening proficiency is determined by the listener's familiarity with the listening environment, listening experience, and utility of the detection task. While the physiological threshold of hearing constitutes the absolute limit of the human ability to detect sound, listening proficiency determines how much poorer the operational threshold is compared to the physiological threshold.

Although auditory signal detection in noise has been extensively studied, few studies have examined the deleterious effect of noise on the human ability to detect real sound sources in operational environments (Abouchacra et al. 2007). In general, sound detection occurs when the signal-to-noise ratio (SNR) at one or more frequencies is larger than 0 dB. However, in cases of narrowband signals and wideband noise the detection may occur at much lower SNRs such as –5 or –10 dB (e.g., Miller et al. 1951; Ollerhead 1971). Abouchacra et al. (2007) investigated detection of the sound of inserting a magazine into an M-16 rifle in a jungle environment (70 dB A-weighted), white (30 dB A-weighted), and pink (70 dB A-weighted) noise and reported average 50% detection thresholds at –10, –12, and –7 dB SNR, respectively. The values for 75% of detections were –7, –9, and –4 dB, respectively, i.e., about 3 dB poorer in all 3 noises.

Letowski et al. (2004) reported that the threshold for an M16 bolt click sound coming from a random direction and presented in pink and jungle ambient background noise averaged –8 dB (pink noise) and –10 dB (jungle noise). The signal detections can be made at even much lower

levels, such as –15 to –20 dB in the case of directional separation between the locations of the target sound source and the directional noise source (Saberi et al. 1991; Good and Gilkey 1992; Abouchacra and Letowski 2004). Pietila et al. (2011) presented a recording of a 6-cylinder diesel engine against a binaurally recorded background of industrial park traffic noise made by cars with gasoline engines. They reported that 9 out of 10 of their listeners could detect the diesel engine at Abouchacra and Letowski 2004; 15 dB SNR. The advantage of spatial separation between the target sound source and directional masker becomes greater in the case where informational masking is added to the energetic masking (Arbogast et al. 2002).

Spiegel and Watson (1981) observed that familiarity with a masker can significantly reduce the amount of informational masking. However, their study was limited to a stationary masker. It is possible that this reduction can be smaller or even eliminated entirely in the case of a time-varying masker such as a naturally changing environmental background that was used in the reported study. It should be expected that the amount of informational masking that adds to energetic masking depends on temporal-spectral variation in both the target sound and the masker (e.g., Oh and Lufti 1999). Further, detection of auditory signals in noise is compromised by even moderate hearing loss or the use of hearing protectors. Price et al. (1989) reported that even such limited loss of hearing acuity can reduce by more than 30-fold the area that a person can successfully monitor for a presence of suspicious sounds and drastically reduce the time left to the person to take action.

Presence of background noise does not only affect auditory detection of target sounds but also absolute visual threshold. Mirabella and Goldstein (1967, p. 283) conducted a literature review on sensory interaction in the context of sonar operator sensitivity and concluded that "the literature provides some evidence that noise affects absolute visual threshold, though the direction and the amount of this effect depend very specifically upon characteristics of both the relevant and the background stimulation."

A common limitation of all the studies discussed above was that they were conducted in laboratory environments. The first large study, and one of the few conducted to date, on sound detection in an open field was conducted by Dobbins and Kindick (1966) in a Panama jungle. Eyring (1945, 1946) and Embleton (1963) earlier measured the sound attenuation caused by the jungle environment, but no perceptual data were collected. In addition, Saby and Thorpe (1946) reported the presence of a significant amount of acoustic energy in the 8,000- to 25,000-Hz range in tropical jungles, but they could not identify any specific source for such sounds. According to Schilling et al. (1947), the Panama jungle is not very different for sound propagation from forests in Pennsylvania, so one may expect that the data found for Panama jungles may be used for estimating transmission loss in forested areas in the United States.

Dobbins and Kindick studied audibility of 63-, 250-, 100-, 400-, and 8000-Hz tones over distances from 7.5 m (25 ft) to 122 m (400 ft). Sound intensity varied from 90.5 dB SPL at 63 Hz to 112.5 dB SPL at 8000 Hz. The authors reported that (1) because of strong masking of high-

frequency energy by the jungle environment, a 1,000-Hz tone was the easiest to detect across all studied distances and (2) during the day low-frequency test signals were detected at levels up to 3–4 dB higher than at night, while high-frequency test signals were detected up to 6–8 dB lower than at night because of changes in the jungle noise spectrum between day and night. Their data indicate that the sound pressure level at the source needed to be increased by 7–15 dB per distance doubling for a signal to be detected in the range of 15 m (50 ft) to 122 m (400 ft).

Hartman and Sternfeld (1973) investigated minimum SNRs required for detecting a flying helicopter (Bell 206A) and reported an average threshold to be about +5 dB SNR. However, they also observed that when ambient noise was high (65–75 dB SPL), the listeners required a smaller SNR for detecting the helicopter than when the noise level was low (50–55 dB SPL). This change corresponded to about a 3-dB decrease in the SNR for high-level ambient noise.

The Army's main interests in auditory detection and recognition are speech and "personnel sounds" produced by individual people or small units. Such sounds typically have strong high-frequency contents (Black 1958; Hodge and Mazurczak 1975) and thus their detection and recognition are very susceptible to noise masking and attenuation by the environment. Typical spectra of several "personnel sounds" are shown in Fig. 4.

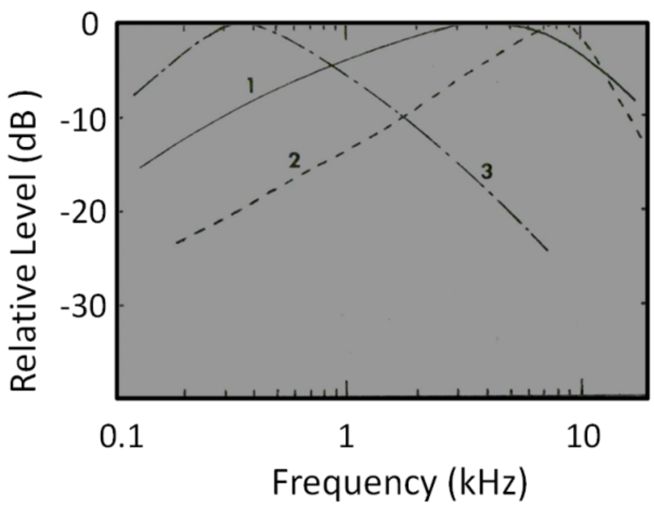


Fig. 4 Spectra of several "personnel sounds" and male speech (Hodge and Mazurczak 1975): 1 = average spectra of 5 sounds peaking at 4000 Hz (canoe paddle; canteen slosh; waves against boat; swimmer leaving water; fish jumping in water); 2 = averaged spectra of 5 sounds peaking at 8000 Hz (steps on grass with and without shoes, loose cartridges carried in pocket of someone moving; loose dog tags jingling; barbed wire being snipped); 3 = male speech.

Coles (1964) conducted a study of audibility of some “personnel sounds” (footstep on leaves, footstep on gravel, water splash, snapped twig, metallic click) and measured detection and recognition thresholds for 2 groups of 10 listeners having normal hearing (NH) and noise-induced hearing loss (NIHL). The average detection thresholds for the NH listeners reported by Coles (1964) are given in Table 5. Coles also observed that the listener’s ability to identify a type of sound at levels just above the hearing threshold was the same for listeners in both groups regardless of their threshold of hearing.

Table 5 The median detection thresholds for 5 “personnel sounds” for normal hearing listeners (n = 10) (Coles 1964). The median speech recognition threshold (SRT) level for phonetically balanced (PB) words is also listed for comparison in the right column.

Median Detection Threshold (dB HL) for Five “Personnel Sounds”					**SRT (dB HL)**
Splash	Footstep on leaves	Footstep on gravel	Snapped twig	Metallic click	
27	37	23	15	24	12

In another study reported by Sheppard and Fishbein (1992) the sound of the idling high-mobility multipurpose wheeled vehicle (HMMWV) could be heard at 100 m but not at 200 m, footsteps on short grass at 15–30 m, and footsteps on gravel at 30–45 m. The authors also reported that the safety switch of the M-16 rifle can be detected as far away as 60–150 m.

4.2 Recognition

Auditory recognition is the ability to determine the type of sound from a closed set of alternatives (speech sounds, vehicle sounds, etc.) while auditory identification extends the recognition task to an open set of alternatives (i.e., what is it?). Very frequently, especially in the layman usage or when the size of the closed set is unclear, the term *recognition* is used for both of these tasks, and such expanded meaning of recognition is used in this report.

The act of sound recognition is based upon previous exposure of the listener to similar signals and the existence of recognition memory. Recognition memory is the ability to recognize previously encountered events and objects (Norman and O’Reilly 2003). There are 2 main theories of recognition memory: single-process theory and dual-process theory. According to the single-process theory, recognition memory is a unidimensional continuum extending from weak to strong memories. The dual-process theory distinguishes between familiarity and recollection as 2 separate processes. One can recognize a certain car as a car seen before (familiarity) and later recognize what kind of car it was and where it was seen before (recollection). Both theories are useful in explaining various memory processes, and both of them can explain memory contribution to decision-making processes in detection and recognition of auditory stimuli. The incoming stimulus must be compared with the number of memory standards, and momentary goodness-of-fit provides input to the decision center (Bernbach 1967).

A sound that has been detected but not recognized may have limited value to the listener. The fact that a sound was heard but not recognized may not result in any action if the person does not know whether this sound belonged to the environment or was created by an extraneous source. Such sound may be a friendly signal, a threat, or may have neutral character.

Recognition (identification) of an acoustic signal arriving at the ear of a listener depends primarily on signal properties, environmental context, state of the listener's hearing, listener's degree of familiarity with the signal, and listener expectations. The acoustic parameters of the auditory signal that are important for sound recognition include temporal envelope, rise and decay times, harmonic structure, frequency spectrum, and its modulation in time. According to Gygi et al. (2007), the 3 main clustering criteria used in sound classification and recognition are harmonicity (harmonic vs. inharmonic structure), onset (impact vs. non-impact onset), and continuity (impulse vs. steady-state character). Conversely, a long-term average spectrum (e.g., formant structure) seems to be a relatively weak cue for sound recognition (Webester et al. 1973; Warren and Verbrugge 1984; Ballas 1993).

There is plenty of evidence that sound recognition, similar to sound detection, is affected by the environmental (implicit or explicit) context in which target sounds are presented (e.g., Ogden and Richards 1923; Southworth 1969; Leech et al. 2009). However, the type and degree of the effect depends on the specific context. Ballas and Mullins (1991) reported that a congruent context significantly aided in correct recognition of target sounds while a misleading or incongruent context and a neutral context impeded correct recognition. Their context scenario consisted of 3 to 6 sounds played in sequence with one of the sounds being the target to be recognized. The other sounds were selected to create a consistent contextual sequence that was or was not congruent with the target sound. The sounds were played in isolation without any background or competing simultaneous sounds. Conversely, Gygi and Shapiro (2007, 2011) and Leech et al. (2009) reported a result opposite to Ballas and Mullins (1991): a positive effect (~5%) of a noncongruent background on sound identification. Gygi and Shapiro (2007, 2011) and Leech et al. (2009) referred to this as the Incongruency Advantage (IA).

Contrary to these previous studies, the authors played target sounds in the background of a continuous scene. When a target sound appeared in the scene, the listener had to write the code identifying the sound (Gygi and Shapiro) or press a button corresponding to the target sound (Leech et al.). In the first case the listeners had to choose a code from a 90-item list; in the second case during each trial, the listener was given a set of 3 sound-relevant pictures to choose from. Gygi and Shapiro (2007, 2011) also reported that the IA effect is SNR-level dependent and does not present itself at low SNR levels (below –15 dB for experienced listeners and below –7.5 dB for naive listeners). However, some caution is advised in considering the IA effect since it may not always apply in real life situations and in listener-free response tasks. For example, a gunshot sound presented in the context of a battlefield environment should be correctly recognized most of the time. However, the same sound heard in the context of a construction site will be most likely classified as a construction sound (e.g., pneumatic hammer) because of

incongruent expectations. Therefore, one needs to be very careful when predicting the effect of ambient background on target recognition.

Sensitivity in detecting signals that are out of context or equally probable in a given environment is independent of the response paradigm, and the listener's response bias is quite conservative. Warren and Verbrugge (1984, p. 705) noted that in the case of sounds that are context independent, they permit accurate identification of classes of sound-producing events when the temporal structure of the sound is specific to the mechanical activities of the source. Age-related hearing loss and cognitive slowing may affect sound recognition abilities of older listeners (VanDerveer 1979). However, Ballas and Barnes (1988) reported that recognition scores in 47 members of organizations of retirees and scores of high school and college students did not differ significantly.

The degree of a listener's uncertainty, also called causal uncertainty (Ballas and Sliwinski 1986), in sound recognition depends on the number of alternatives available in the listening context to the listener in making decisions regarding the sound source. A good measure of the listener's uncertainty is the listener's response time. According to Ballas and Sliwinski (1986) both measures are linearly related. A listener's uncertainty is also related to the ecological frequency of the sound in a given environment. Ecological frequency has been defined by Ballas (1993) as the expected rate of occurrence of the target sound in a given environment. High ecological frequency increases the rate of accurate recognitions but mainly in the case of a family of sounds that have similar acoustic properties. Such sounds are characterized by high confusability or high casual uncertainty. Sounds that have unique acoustic parameters are easily recognizable even if their ecological frequency is low. Such sounds build apparently very strong mental prototypes in the brain that are easy to recall. Even the infrequent appearance of such sounds enforces their stereotypes and constrains the casual uncertainty associated with the sound (Ballas 1993).

One additional issue with sound recognition experiments involving non-speech sounds is that the sounds used in a study may have different identifiability. In the case of an auditory recognition task, identifiability can be loosely defined as the probability that the listeners can correctly identify the sound source, or the type of sound, while listening to the sound in optimal listening conditions.

In general, identifiability of a specific sound in a set can be defined as causal uncertainty entropy, H, defined as

$$H = -\sum_{i-1}^{n} p_i \, log_2 \, p_i, \qquad (10)$$

where p_i is the proportion of events of category i and n is the number of categories. Perfect identifiability corresponds to uncertainty of identification H = 0. Poor identifiability can be caused by either a lack of listeners' familiarity with the sound or a poor exemplar of the sound (e.g., poor recording). It is imperative that all sound targets used in detection and identification studies have perfect identifiability. This is, however, not always the case. Lass et al. (1982) and

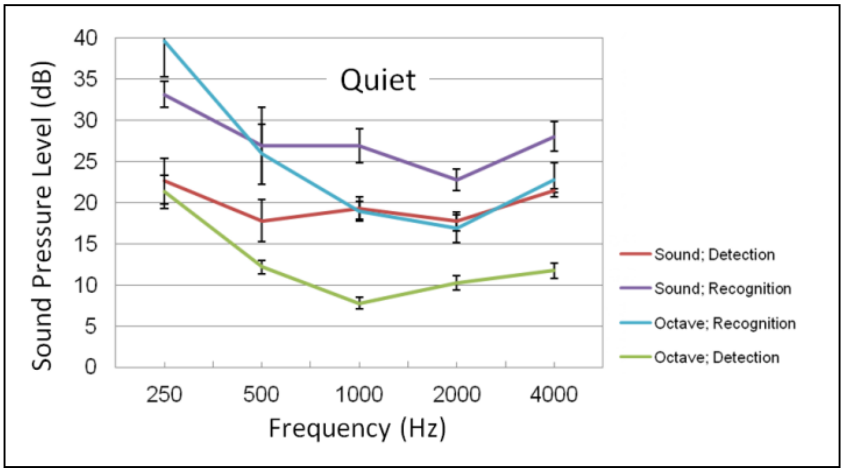
Ballas et al. (1987) compared identifiabilities of a number of sounds that have been used in test materials or were taken from commercial sound effect records and reported that some of them had compromised identifiability. Some of the sounds were hard to recognize because of the unfamiliarity of the listeners with the sounds (e.g., pig grunting, sheep bleating, donkey braying) and some due to uncharacteristic or poor recording (e.g., drum, motor scooter, bus moving off). Therefore, it is required at the beginning of any target recognition experiment to ensure that all the targets used in the study have uncompromised identifiability.

There have been only a handful of studies attempting to determine both detection and recognition thresholds of environmental sounds in natural backgrounds. Kobus et al. (1986) investigated single- and multimodal detection and recognition of sonar targets by sonar operators and reported auditory detection and recognition thresholds at –12.2 and –10.8 dB (background sea noise; Koss PRO-4-AAA earphones), respectively. Myers et al. (1996) conducted a large study of 25 octave-filtered environmental sounds and measured their thresholds of detection and recognition in quiet and in 60-dB A-weighted 20-voice multitalker noise (see Frank and Craig 1984). For each sound an octave band that was the most important for sound recognition was selected (250, 500, 1000, 2000, or 4000 Hz) and all octave-filtered sounds were fully identifiable when presented to each listener at the listener’s most comfortable listening level.

A second part of this study using the same unfiltered sounds and data collected at the same time was published later by Abouchacra et al. (2007). The average detection and recognition thresholds in quiet and in noise for all environmental sounds reported in both parts of this study are shown in Fig. 5, and the differences between corresponding recognition and detection thresholds are shown in Fig. 6.

Detection thresholds shown in Fig. 5 for octave-filtered sounds were relatively similar to thresholds for pure tones measured for study participants. Informal responses from the participants indicated that they needed both temporal and spectral information to recognize the sounds. The results of both studies show a common picture that most of the sounds are recognized when presented 5–10 dB above their detection thresholds except for very low-frequency sounds that may need to be heard as much as 20 dB above the detection threshold to be recognizable. These data agree with Egan’s (1948) observation that speech sounds need to be 8 dB above their detection threshold to be recognizable.

All reported sound recognition studies were conducted in a laboratory setting using loudspeaker or earphone sound reproduction. No study has been found to report similar data collected in an outdoor environment.



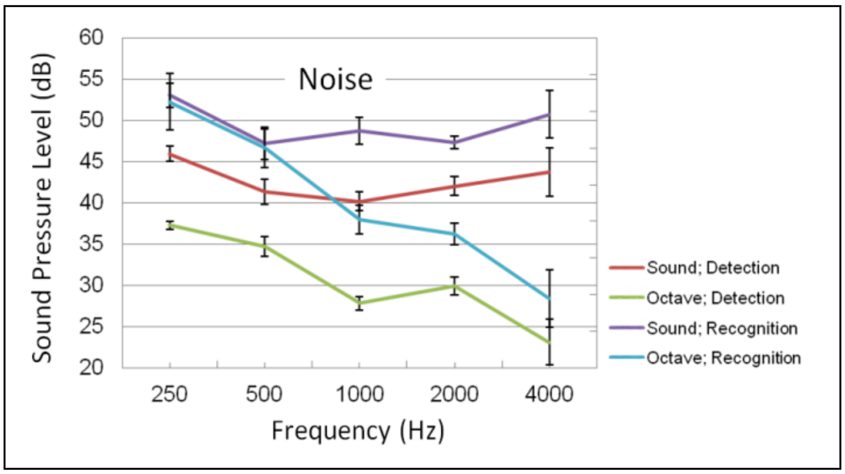


Fig. 5 Detection and recognition thresholds for octave-filtered (octave) and unfiltered (sound) environmental sounds. Both filtered and unfiltered sounds have been grouped by the center frequency of their prefiltered octave and average values for each subgroup are displayed as a function of this frequency. Vertical lines represent standard error. After Myers et al. (1996) and Abouchacra et al. (2007).

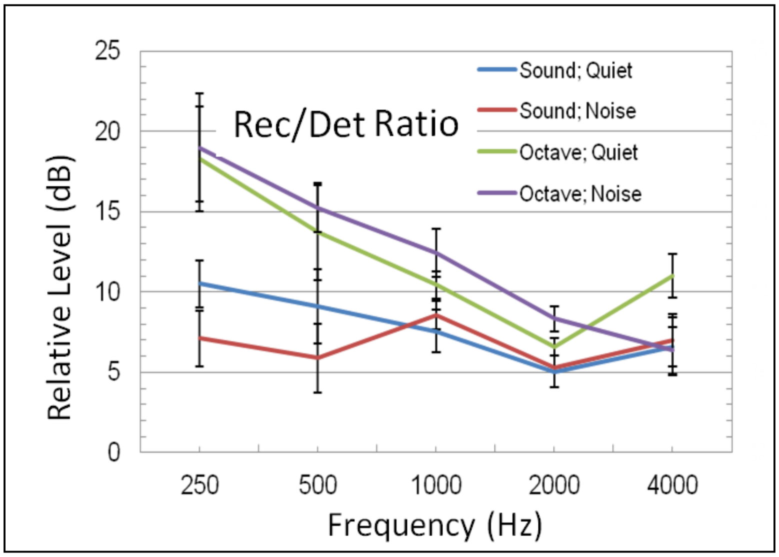


Fig. 6 Differences between mean recognition and detection thresholds in quiet and noise. The sounds are displayed according to the center frequency of their filtered octave and are represented by black squares. Both filtered and unfiltered sounds have been grouped by center frequency of their prefiltered octave, and average values for each subgroup are displayed as a function of this frequency. Vertical lines represent standard error. After Myers et al. (1996) and Abouchacra et al. (2007).

4.3 Spatial Perception

Spatial perception is not a theme of this report, but it is addressed very briefly here since it was also a part of the whole study. Spatial perception of sound involves localization of sound sources (directional localization and distance estimation) and determination of the spaciousness of the surrounding environment. Directional localization ability is the most studied element of spatial perception in scientific literature, but in this study, it was only measured in a very limited angular range, and the data will be reported later elsewhere. Theoretical considerations regarding directional localization studies can be found in Letowski and Letowski (2012).

Auditory distance estimation has also been studied vigorously for decades but only for very short distances and predominantly in closed spaces. Auditory distance estimation ability was also addressed in the current study. However, the current study was the first one, to the authors' knowledge, to address distant sound sources in a large open space. Because of the novel character of the auditory distance estimation investigation portion of the study, an extensive discussion of the results has been published separately by Fluitt et al. (2013).

Sound spaciousness is an element of sound perception most relevant to and important for closed spaces and therefore has not been addressed in the current study. It will be investigated and addressed in the context of closed spaces separately from studies involving an open space.

5. Spesutie Island Study: Study Description

The sound detection and recognition data were collected as a part of the Spesutie Island Study, which was named for the location where the study was conducted. In addition to sound detection and recognition judgments, the listeners performed distance estimation judgments that were the main part of the study, and these results are described in a separate report (Fluitt et al. 2013).

The Spesutie Island Study was conducted at Spesutie Island on Aberdeen Proving Ground, MD, in a grassy outdoor test area known as the EM Range. The EM Range is an open field approximately 900 m long and 200 m wide. The range is flat, covered with grass, and includes a sand/gravel track encircling the grassy area. Three sides of the area are surrounded by young trees and bushes, and the fourth side is separated by an additional 50 m of grassy area separating the EM Range from a local road. The general view of the area is shown in Fig. 7.

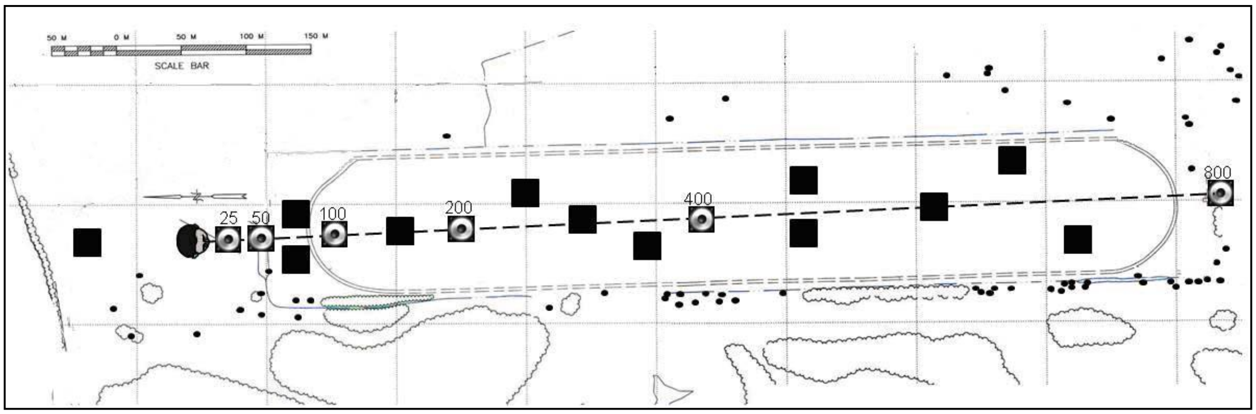


Fig. 7 Outdoor test area on Spesutie Island where the study was conducted. The human head represents the listening station, squares with numbers next to them represent active loudspeakers and respective distances in meters from the listener, and black squares without numbers represent dummy loudspeakers. Some elements of the figure are not to scale.

5.1 Instrumentation

The Spesutie Island Study was conducted using a desktop PC, TDT System II Signal Processing System, Sony T77 DAT recorder, and supporting hardware and wiring. All equipment used by the listener and needed for monitoring acoustic conditions was located at the listening station shown in Fig. 8. Auxiliary equipment not used at the listening station was located in a trailer at the north end of the range, 50 m to the left of the listening station (not shown in Fig. 7). Proprietary in-house software was used to control the experiments, present sounds, and collect listener responses.

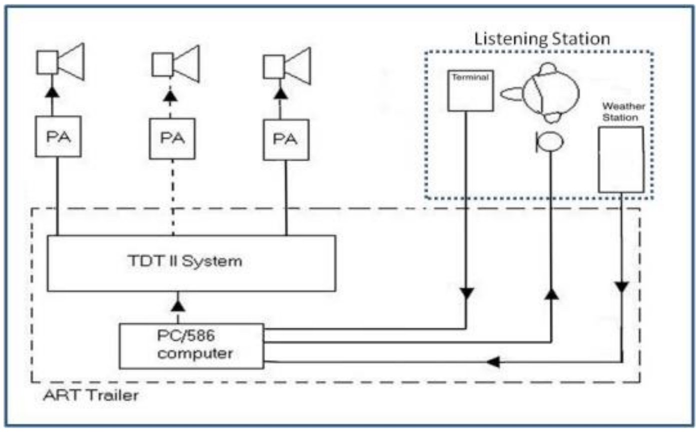


Fig. 8 Block diagram of the instrumentation used in the study

The listening station consisted of a table, chair, monitor, keyboard, and mouse. The station was situated on a concrete slab, protected from sun and bugs by a 2.1-m-high acoustically transparent canvas canopy with side walls made of bug netting. The station was also equipped with a Brüel and Kjaer 4133 microphone and a Davis Monitor II weather station. The microphone, mounted in an upright position 0.3 m (1 ft) to the left of the listener, was used to record actual background noise and test signals during each sound presentation. A weather station, positioned 2 m to the left of the listener, was used to monitor temperature, humidity, wind strength, and wind direction. The data were automatically recorded in the listener file and were used to assess the effects of meteorological variables on sound propagation (see Fig. 8).

Eighteen boxes were scattered along the field within ±15° of the main listening axis of the listener (see Fig. 7). The boxes were made of wood with a removable front panel covered with acoustically transparent cloth. Six of the loudspeaker boxes housed test loudspeakers, and the other boxes served as decoys. The boxes that contained the test loudspeakers were located 25, 50, 100, 200, 400, and 800 m away from the listening station (see Fig. 7). The loudspeakers were Electro-Voice Sx500+ stage monitors capable of delivering approximately 120-dB peak SPL at a 1-m distance from the loudspeaker. Loudspeakers were fed from Crown 2400 power amplifiers.

5.2 Listeners

Twenty-four (12 male and 12 female) listeners between the ages of 18 and 25 participated in the study (M = 21.4; SD = 3.6). The participants were recruited from the civilian population of Aberdeen Proving Ground and local colleges. All listeners had pure-tone hearing thresholds better than or equal to 20-dB hearing level (HL) at audiometric frequencies from 250 through 8000 Hz (ANSI 2010) and no history of otologic pathology. The pure-tone average threshold, calculated as the mean of hearing thresholds at 500, 1000, and 2000 Hz, was 1.2-dB HL for the entire group of listeners (48 ears) and varied from –5.0-dB HL to 8.3-dB HL for individual listeners. The difference between pure-tone thresholds in both ears was no greater than 10 dB at

any test frequency. The listeners had no previous experience in participating in psychophysical studies. The average hearing threshold data for the entire group of participants are shown in Fig. 9.

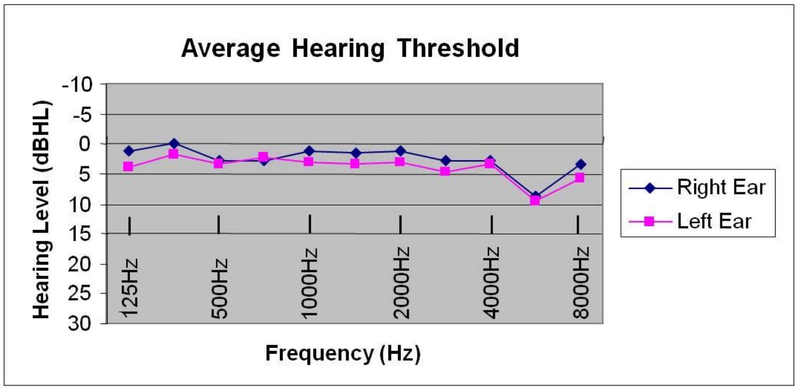


Fig. 9 Average hearing threshold data for the group of 24 participants

5.3 Sound Sources

Eight natural test sounds representing various sound sources were used in the study. The set consisted of 7 environmental sounds and the word "Joe" whispered by a male talker. Environmental sounds can be defined as sounds produced by real sound sources (events), both as intended signals or as by-products, that have meaning by association with these sound sources (events) (Ballas and Howard 1987). Each sound had an overall duration of less than 1 s. All sounds were recorded by the authors, except the generator and rifle shot sounds, which were recorded during a different study. The recordings were made with an ACO 7012 microphone and a Sony T77 DAT tape recorder. The respective A-weighted sound pressure levels of the recorded sounds were measured during sound recording. These levels were recalculated for a 1-m distance from the sound source and are listed in Table 6. The same sound levels measured at a 1-m distance in front of a loudspeaker were used in the study. The only exception was the rifle sound, which had a sound pressure level that was too high at a 1-m distance (124 dB A) to be reproduced and was scaled down by 30 dB to 94 dB A. Spectral and temporal characteristics of all the sounds are shown in Fig. 10.

Table 6 List of test sounds and their production levels at 1-m distance from the sound source

Sound	Sound Description	Sound Level (dB A)	Sound Level (dB SPL)
Bolt click	Rifle bolt closure	83	84
Dog bark	Dog bark	88	89
Generator	Generator noise	74	83
Joe	Male whisper "Joe"	72	76
Car horn	Car horn	95	95
Rifle	Rifle shot	94	96
Throat	Throat sound	74	76
Splash	Water splash	73	81

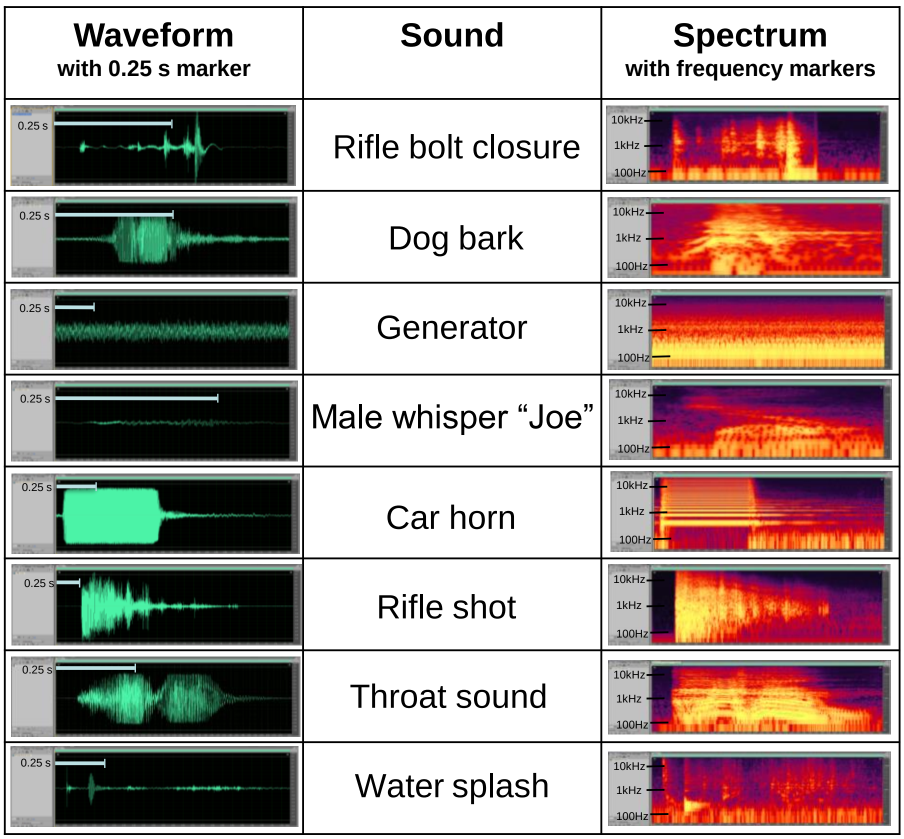


Fig. 10 Temporal and spectral characteristics of the sounds used in the study

5.4 Procedure

During the study the listener was seated at the listening station and was asked to listen to incoming sounds and respond using a computer keyboard and mouse. The listeners listened to the environmental background and isolated the incoming target sound from the background (detection) and matched it to one of the memory standards (recognition). An individual test trial

consisted of (1) a warning period indicating the beginning of a new test trial, (2) an observation period, and (3) a response period. A yellow-red-green status system light was built into the graphical user interface located on the monitor in front of the listener. The light was used to indicate the warning period (yellow light, 1 s), the observation period (red light, 10 s), and the response period (green light) when listeners recorded their responses. The length of the response period was not predetermined, and listeners could use this time to take short breaks. Listeners were also asked to wait prior to starting the next trial in the presence of occasional extraneous sounds, such as an airplane flying over or a car passing by, that could interfere with the performed task. To start the next trial, the listener used the mouse to select the “GO” button on the monitor and activate the yellow light that indicated the beginning of the new observation period.

During each observation period, a single test sound or no sound at all was presented. The sound lasted less than 1 s and could appear at any time during the observation period. The time when the sound appeared within the observation period was randomized. During the response period, the listener was asked (1) to indicate if a sound was present and (2) to identify the presented sound using a 12-item closed-set list of alternatives (which included all the sounds presented in Table 6, plus bird, car engine, airplane, and other). The third task, described separately in Fluitt et al. (2013), involved auditory distance estimation. No response feedback was given to the listeners, but the listeners were told that some sounds may appear very often while others may appear occasionally or not at all.

Instructions regarding individual responses and the templates for response input were provided on the computer screen. Prior to the experiment, the specific sounds used in the study plus several others listed on the list of alternatives were demonstrated to the listener from a nearby loudspeaker, and a short training session was conducted.

One listening block included all 8 sounds presented from all 6 loudspeakers with 4 repetitions each. In addition, 48 blank (no sound) trials were randomly presented in each block, resulting in 240 test trials per block. The responses made during the blank trials are not included in the presented data analysis. The order of sounds in each listening block was randomized. Four listening blocks were presented to each listener during a single listening session. The duration of the listening session depended on the duration of the rest periods taken by the listener but was typically 3.0 to 3.5 h.

5.5 Environmental Conditions

The study was conducted during a 2-week period in August. Historically, weather conditions in August at Aberdeen Proving Ground, MD, (Spesutie Island area; sea level altitude) are relatively stable with average relative humidity varying from a low value in the upper 50% range in the morning to a high value in the upper 80% range in the afternoon (mean value 71%). The average temperature during the day varies between 22 and 26 °C (mean value 24.1 °C). The wind conditions are characterized by the lowest average wind velocity throughout the year (about 5–6 km/h)

(Monthly humidity . . . 2012; Average temperatures . . . 2012). The Maryland Department of Natural Resources reports that there are over 400 species of birds and an untold number of insects inhabiting the area surrounding the test site (Maryland plants . . . 2012). Sounds made by many of these species created the ambient noise floor that served as a backdrop for our study. The time and temperature of the day also contributed to the acoustic behaviors of some of the wildlife. Many of the insects that contributed to our background sounds were crickets, katydids, cicadas, bees, beetles, and grasshoppers. The average weather and noise conditions observed during the study are listed in Table 7. The averages are mean values of the average conditions for individual listening sessions (sampled at every sound presentation). The overall weather conditions were a bit warmer and drier than average for the area, resulting in an average heat index of 31 °C.

Table 7 Mean, median, and standard deviation values of the weather and noise conditions during data collection

Parameter	Mean	Median	Standard Deviation	Unit
Temperature	28.5	29.0	2.3	°C
Relative humidity	67.6	68.0	10.2	%
Atmospheric pressure	1.005	1.006	0.018	Atm
Wind velocity	5.3	4.6	2.3	km/h
Wind direction	150.0	159.0	37.6	°
Noise level	50.7	53.0	5.2	dB A

The refractive conditions during individual listening sessions were consistent. The temperature varied within 2 °C, relative humidity within 10%, and in most cases the wind direction was stable and wind speed changes were within 2 km/s. Stronger wind usually came from the south and southeast directions, while periods of weak wind came from the other directions. This behavior resulted in the relatively large standard deviation in the wind direction parameter in Table 7. The background noise at the listening station varied between 35 and 60 dB A-weighted depending on the time of the day and weather conditions, with many insects producing sounds in the range of 4–8 kHz. In general, the insects have unique comfort temperature zones in which they tend to make their calls. For example, for cicada *Tibicina*, the comfort temperature zone is 22–24 °C (Sueur and Sanborn 2003). In addition, some insects (e.g., crickets) made calls with frequency of chirps directly related to the temperature (e.g., Toms 1992). As the temperature becomes higher, the chirp rate also becomes higher.

6. Spesutie Island Study: Results and Discussion

Since the goal of the study was to simulate natural sound sources as closely as possible and to learn some basics about the detectability and recognizability of real sound sources in an open space, all recorded sounds were reproduced at their natural recorded levels (except for the rifle shot). This means that each sound was produced at only a single level (see Table 6) by all loudspeakers regardless of the distance of the loudspeaker from the listener. As a consequence, not all the sounds were heard and properly recognized by all listeners when emitted from distant loudspeakers. The variable audibility of sounds was also exacerbated by changes in weather conditions across the study. This was the expected constraint of the implemented study design focused on natural production levels. The sound events and their levels were selected arbitrarily as well, but they were representative of specific sound sources. The selected experimental design focused on sound production level (as opposed to presentation level). Sound production level is considered important in studying how sound propagation in an open field affects perception of a given sound source.

6.1 Effects of Sound Type

Mean percentages of detections and correct recognitions as functions of the distance from the sound source are shown in Figs. 11 and 12. The data have been averaged across all listeners regardless of the weather condition.

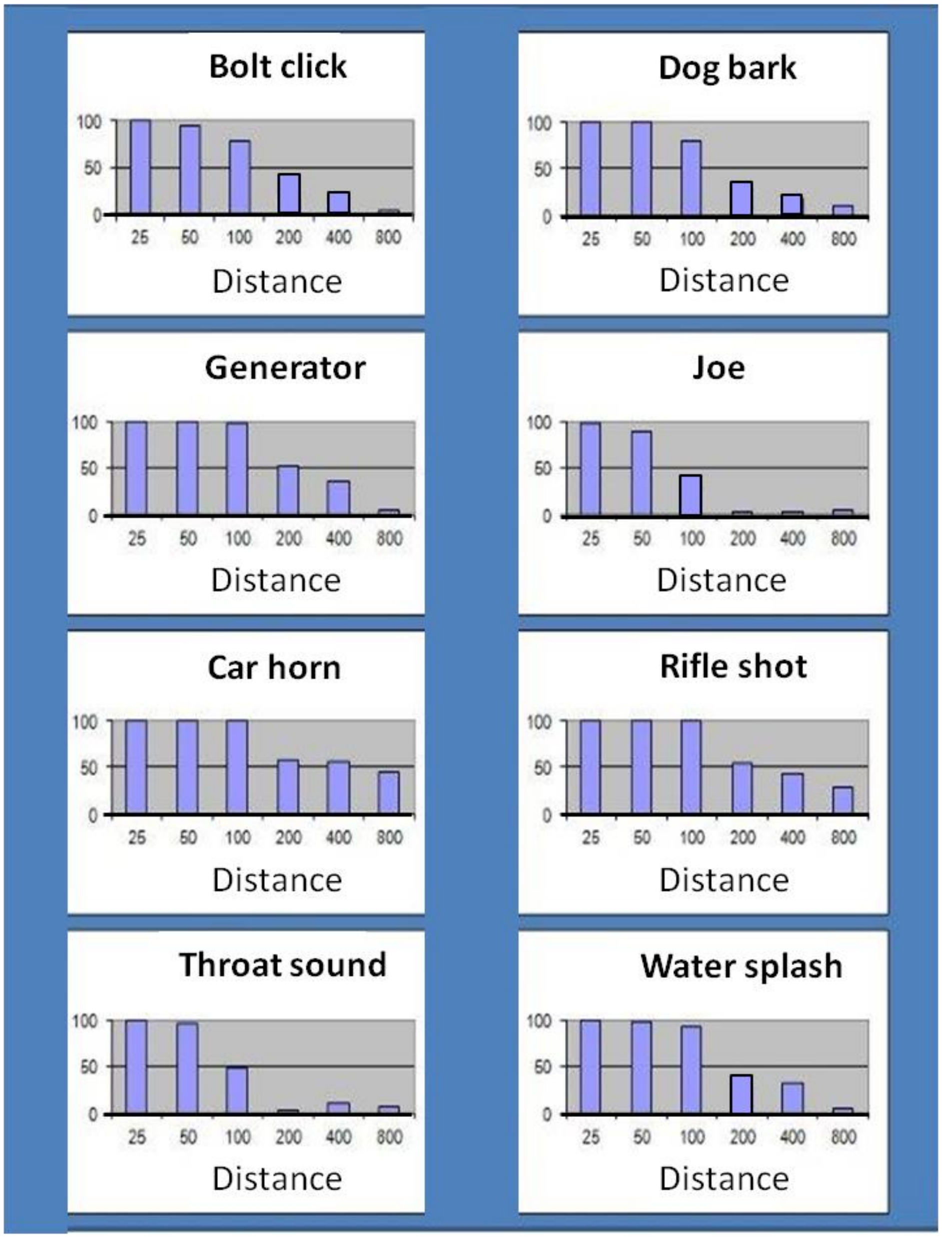


Fig. 11 Bar graphs showing percentages of detections for all the sounds used in the study as functions of the distance (in meters) to the sound source

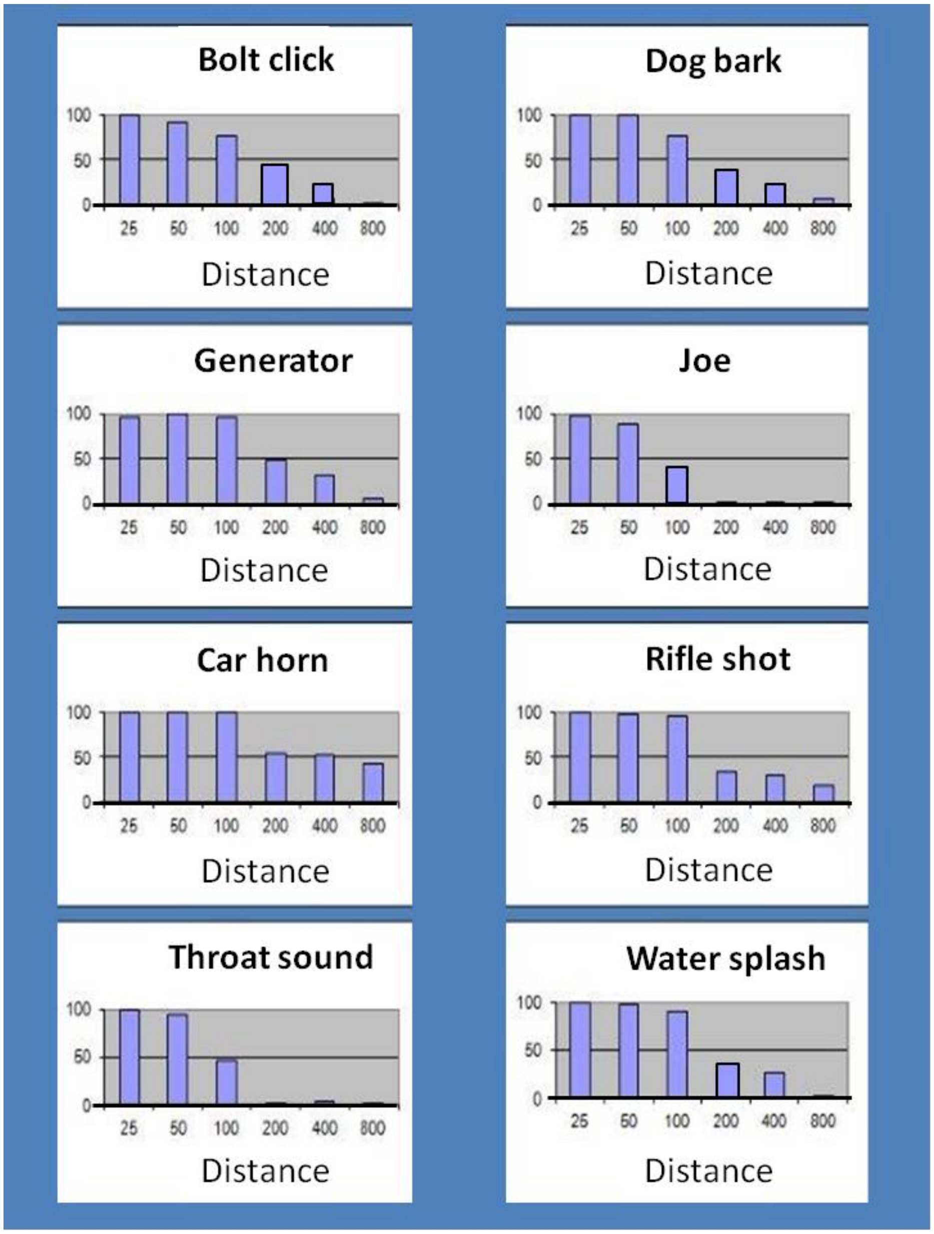


Fig. 12 Bar graphs showing percentages of correct recognitions for all the sounds used in the study as functions of the distance (in meters) to the sound source

The data shown in Figs. 11 and 12 have been used to calculate detection and recognition distance thresholds. For each sound dataset shown in these figures a logistic function was fitted and a 50% detection or recognition threshold determined. Since some of the trials were "empty" (no sound was emitted) and listeners had more options to respond than the number of sounds that were actually used in the study, no correction for guessing in determining recognition thresholds has been applied. The distances to the sound source corresponding to the 50% detection and recognition thresholds are shown in Table 8.

Table 8 Detection and recognition distances (p = 50%) for the sound signals used in the study

Sound	Detection Distance (m)	Recognition Distance (m)
Rifle bolt closure	148	143
Dog bark	158	154
Generator	233	195
Male whisper “Joe”	80	77
Car horn	640	612
Rifle shot	280	160
Throat sound	98	95
Water splash	165	165

The data in Table 8 indicate that most of the sounds were immediately recognized after detection. The only exceptions were the rifle shot and to some extent the sound of the generator.

The quartile deviations (25% and 75% probability of perception) for all the threshold distances shown in Table 8 are listed in Tables 9 (detection) and 10 (recognition). They indicate relative variability in detecting and recognizing specific sound sources by the participating group of listeners.

Table 9 Quartile deviations and means of the threshold detection distances for 8 sounds investigated in this study

Sound	Lower Quartile (m)	Detection Distance (m)	Upper Quartile (m)
Rifle bolt closure	230	148	80
Dog bark	280	158	100
Generator	490	233	150
Male whisper “Joe”	120	80	50
Car horn	800	640	365
Rifle shot	640	280	160
Throat sound	160	98	60
Water splash	350	165	100

Table 10 Quartile deviations and means of the threshold recognition distances for 8 sounds investigated in this study

Sound	Lower Quartile (m)	Recognition Distance (m)	Upper Quartile (m)
Rifle bolt closure	220	143	70
Dog bark	250	154	90
Generator	440	195	125
Male whisper “Joe”	115	77	45
Car horn	800	612	240
Rifle shot	400	160	120
Throat sound	150	95	60
Water splash	320	165	100

Most of the natural levels of sounds were detected/recognized at distances about 85–165 m away from the sound source. It may be hypothesized that somewhere in this range lies humans’ safety perimeter—that is, the distance at which humans are warned about potential natural danger in the environment caused by local events and objects.

The spectra of all the sounds measured at 1 m away from the loudspeaker are shown in Fig. 13.

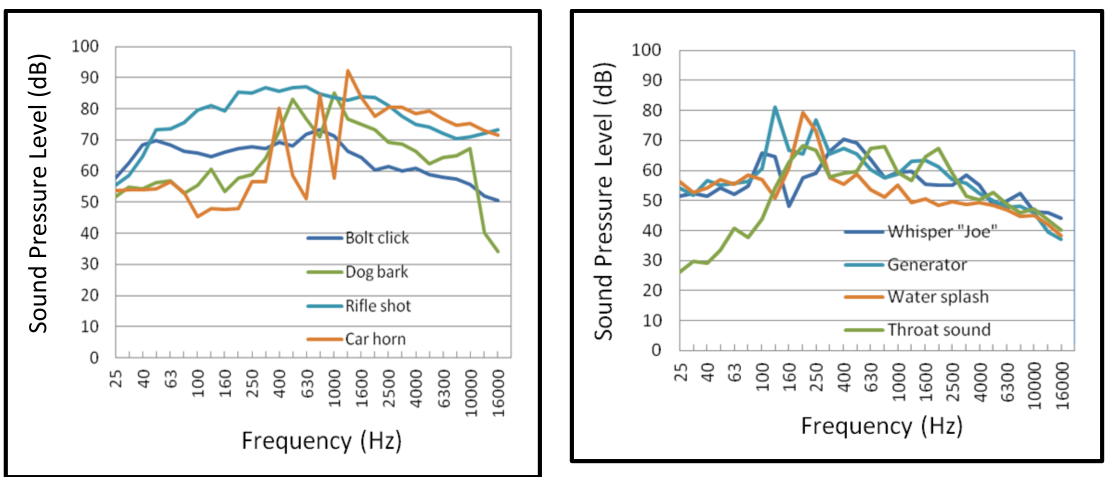


Fig. 13 Spectral envelopes of all the sounds measured 1 m away from a loudspeaker. The spectra and their levels should be the same as originally recorded except for the rifle shot sound.

The actual spectra of barely detectable sounds arriving at the listener’s location could not be reliably measured. The sound spectra envelopes were generally below the envelope of existing environmental noise, and both the sounds and noise spectra varied depending on the actual weather conditions. Therefore, the spectra are not reported here. The overall sound attenuation during sound propagation varied depending on the type of sound from 5 dB (water splash) to 8 dB (dog bark) per doubling of distance. Table 11 lists approximate overall sound pressure levels at the listener position corresponding to the threshold distances listed in Table 8.

Table 11 Sound pressure levels at the listener location corresponding to detection and recognition thresholds of the sound used in the study

Sound	Detection Level (dB SPL)	Recognition Level (dB SPL)
Rifle bolt closure	48	48
Dog bark	30	30
Generator	44	46
Male whisper “Joe”	38	38
Car horn	30	30
Rifle shot	39	44
Throat sound	36	36
Water splash	41	41

6.2 Effects of Temperature, Humidity, and Atmospheric Pressure

The 2 main weather parameters investigated and recorded in this study were temperature and relative humidity. Temperature is the measure of the average amount of kinetic energy in the body or environment expressed on a normalized scale. Relative humidity is the ratio of the amount of moisture in the air to the total amount of moisture that can be held at a given temperature—that is, the degree of saturation of air with moisture.

To assess the effects of temperature and humidity on auditory detection and recognition, the data were divided into binary categories (low and high) for each variable. However, note that the effects of temperature and relative humidity on sound absorption are nonlinear and mutually dependent, and their interrelation affected the results of the described analysis. The interdependence of temperature and relative humidity effects and attenuation of propagating sound is shown in Fig. 14.

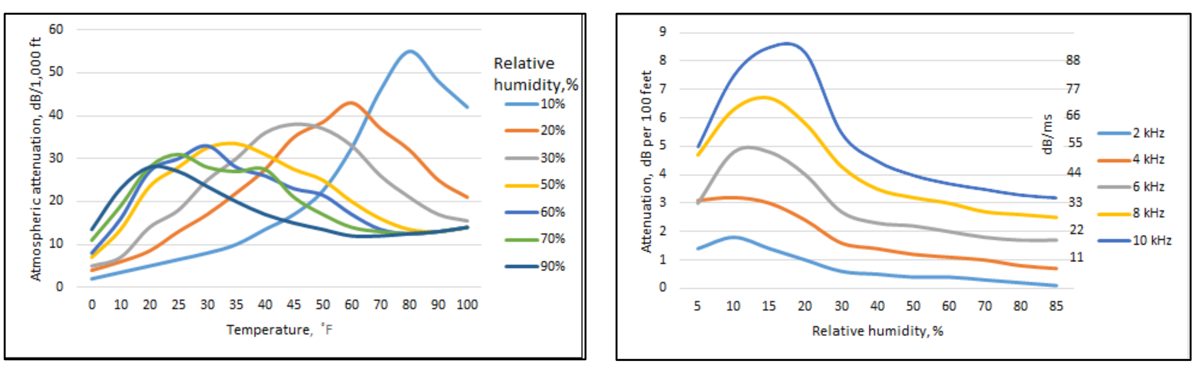


Fig. 14 The effects of temperature and relative humidity on sound attenuation as functions of temperature (left panel, adapted from Beraneck [1971]) and humidity (right panel, adapted from Eagle and Forman [2002]).

The 4 extreme weather conditions have been named Hot, Cool, Dry, and Humid, and their temperature and humidity ranges are listed in Table 12. These names are only the labels, and they do not represent the actual weather conditions. The whole range of outdoor temperatures was very high, reaching into code red (category IV) of the Wet Bulb Globe Temperature (WBGT) heat index flag conditions (AFPAM 48-151 2002). The lowest temperature was 24 °C, so the terms *cold* and *hot* have just a relative meaning. The conditions listed in Table 12 are just the extreme conditions in relation to weather conditions experienced during the study.

Table 12 Extreme weather conditions (temperature and relative humidity) recorded during the study

Type of Weather	**Temperature Range (°C)**	**Relative Humidity Range (%)**	**Average Temperature (°C)**	**Average Relative Humidity (%)**
Hot	29–34	55–75	31	64
Cool	24–27	65–88	25	78
Dry	24–33	50–62	28	61
Humid	24–27	77–98	26	80

For weather conditions listed in Table 12, the sound attenuation due to relative humidity and temperature can be neglected at low frequencies below 500 Hz. The sound attenuation coefficients at 1000, 2000, 4000, and 8000 Hz are approximately 6, 12, 25, and 40 dB/km (UFC 2003, p. 5-3). We analyzed sound detection and recognition data obtained under the weather conditions listed in Table 12 by comparing data collected during pairs of each opposite conditions: hot (5 listeners) and cool (5 listeners) and dry (4 listeners) and humid (4 listeners). The detection distances for each of the sounds under humid-average-dry and hot-average-cool listening conditions are listed in Tables 13 and 14, respectively. Recognition data are not reported here since the recognition distances are almost the same as detection distances.

Table 13 Detection distances (meters) for humid-average-dry weather conditions

Sound	**Humid**	**Average**	**Dry**
Rifle bolt closure	145	148	100
Dog bark	200	158	110
Generator	240	233	200
Male whisper “Joe”	90	80	60
Car horn	600	640	180
Rifle shot	575	280	160
Throat sound	135	98	80
Water splash	265	165	140

Table 14 Detection distances (meters) for hot-average-cool weather conditions

Sound	Hot	Average	Cool
Rifle bolt closure	145	148	165
Dog bark	150	158	180
Generator	280	233	440
Male whisper “Joe”	60	80	100
Car horn	800	640	430
Rifle shot	345	280	430
Throat sound	95	98	120
Water splash	150	165	295

Hot-Cool: The detection distances for all sounds except car horn were shorter at the Hot condition than at the Cool condition. This indicates that the increasing air absorption affected listener responses to a greater degree than the decreased noise level. Additionally, the Hot data were very close to the Average data, indicating that the effect of temperature above the average temperature had a minimal effect on listeners’ perception.

The average detection distance for car horn was about 2.0 times longer at the Hot condition than at the Cool condition. This indicates that the masking effect of the increased noise level at the Cool condition affected the perception of the car horn sound more than changes in air absorption. This may be due to the high frequency content of both the car horn sound and insect noise.

Dry-Humid: All detection distances at the Dry condition were shorter (much shorter for car horn and rifle shot sounds) than at the Humid or Average condition. The detection distances for the Humid condition were very similar to those of the Average condition except for the rifle shot sound.

During data collection, we expected to observe some effects of the time of the day and related changes in temperature on the detection and recognition of target sounds. Namely, in the morning when the temperature was lowest near the ground, causing bending of sound waves toward the ground (downward refraction), it should have resulted in slightly better audibility of far away sources. Conversely, in the afternoon when the temperature was highest near the ground, causing the sound waves to bend upward (upward refraction), we expected poorer audibility of far away sounds in comparison to early morning data. However, we did not observe such trends. This is most likely due to the confounding effects of air humidity, varying insect noise, and relatively few observations made at extreme weather conditions.

6.3 Effects of Wind

Wind is one of the major factors affecting sound wave propagation in the environment. Wind effects are quite complex, fast changing (e.g., wind gusts), and confounded by other weather conditions, and as a result, it is hard to assess wind effects in studies like the current one. Therefore, it was important for this study that all data collection was limited to relatively stable

and weak wind conditions. The average wind speed throughout the study was 5.3 km/h (median = 4.6 km/h), with wind out of the average direction of 150° (SSE direction). On the Beaufort wind force scale, most wind conditions recorded in the study ranged between 0 km/h (calm: less than 1 km/h) and 1 km/h (light air: between 1 and 5.5 km/h). There were 9 sessions with stronger winds ranging from 5.8 to 9.8 km/h, but in all cases except one (side wind; no strong perceptual effects), they were cases of the wind blowing downwind (i.e., with the direction of propagating sound). This limited the analysis of wind effects to only a comparison between data collected during strong downwind conditions (8 cases) and data collected during no-wind and low-strength-wind conditions (15 cases; 0 to 5.15 km/h; various wind directions). The detection and recognition threshold distances calculated for no-wind and downwind conditions are shown in Tables 15 and 16. The average wind speeds for no-wind and for downwind conditions were 3.9 km/h (SD = 1.0 km/h) and 8.2 km/h (SD = 1.2 km/h), respectively. The effects of wind speed on detection distance and recognition distance are shown in Tables 15 and 16.

Table 15 Effects of no-wind and downwind conditions on detection distances (meters) for all the sound sources investigated in this study. The overall average distances are also included in the table for comparison.

Sound	**No-Wind Condition**	**Overall Average**	**Downwind Condition**
Rifle bolt closure	97	148	200
Dog bark	99	158	200
Generator	202	233	200
Male whisper “Joe”	75	80	97
Car horn	400	640	>800
Rifle shot	200	280	400
Throat sound	85	98	109
Water splash	160	165	205

Table 16 Effects of no-wind and downwind conditions on recognition distances (meters) for all the sound sources investigated in this study. The overall average distances are also included in the table for comparison.

Sound	**No-Wind Condition**	**Overall Average**	**Downwind Condition**
Rifle bolt closure	94	143	200
Dog bark	94	154	200
Generator	185	195	200
Male whisper “Joe”	75	77	88
Car horn	400	612	> 800
Rifle shot	154	160	172
Throat sound	80	95	104
Water splash	152	165	200

Interquartile ranges (IQRs) for the wind data in Tables 15 and 16 are given in Table 17.

Table 17 Interquartile ranges (IQRs) for threshold detection and recognition distances under no-wind and downwind conditions

Sound	No-Wind Condition		Downwind Condition	
	Detection	Recognition	Detection	Recognition
Rifle bolt closure	91–108	91–103	163–268	152–265
Dog bark	92–108	91–103	154–304	163–265
Generator	163–265	161–265	161–282	154–278
Male whisper “Joe”	93–101	68–88	90–105	74–103
Car horn	173–x	168–x	x–x	x–x
Rifle shot	161–268	132–240	175–x	130–258
Throat sound	75–98	55–87	89–128	84–125
Water splash	156–186	132–175	147–304	153–289

Note: x = distance longer than 800 m.

The data shown in Tables 15–17 indicate that downwind sound propagation as expected improved both detection and recognition ranges of all the sound sources. The greatest increase, approximately 2-fold, was observed in cases of the sounds of the rifle bolt click, dog bark, and car horn—that is, the sounds that were heard from the largest distances at all conditions. This 2-fold increase in detection and recognition distances resulted from an approximately 2-fold change in average wind velocity from about 3.9 to 8.2 km/h. However, this 2-fold proportionality should not be generalized since the downwind data have only been collected from 5 listeners and should only serve as a guide for further studies.

6.4 Effect of Background Noise

The background noise that affected the audibility of sounds produced by loudspeaker-simulated sound sources was, for the most part, the noise produced by ever-present insects. Occasional sounds produced by birds, other animals, distant cars, and overflying airplanes were relatively rare, quite distinct, and usually quite short. They could affect 1 or 2 of the specific judgments, but they did not contribute significantly to the continuous noise present in the field. The average noise level across the study was about 51 dB A-weighted and was dependent on the weather conditions and time of the day. Typically, as the day became warmer, insect activity decreased, making the afternoons quieter than the mornings. As a result, most sounds were less audible during mornings than during hotter afternoons. The relationship between the noise level and air temperature recorded throughout the study is shown in Fig. 15.

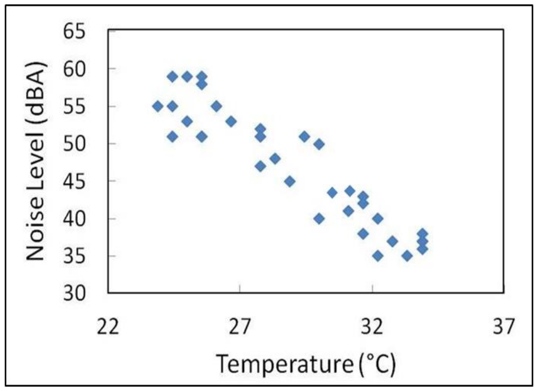


Fig. 15 Relationship between background noise level (insects' calls) and air temperature measured during the study

The spectral properties of the background noise are shown in Fig. 16. The insects' calls were most intense in the frequency band from about 4 to 8 kHz, and the number of calls in the frequency range from approximately 1.5 to 8 kHz greatly decreased with temperature.

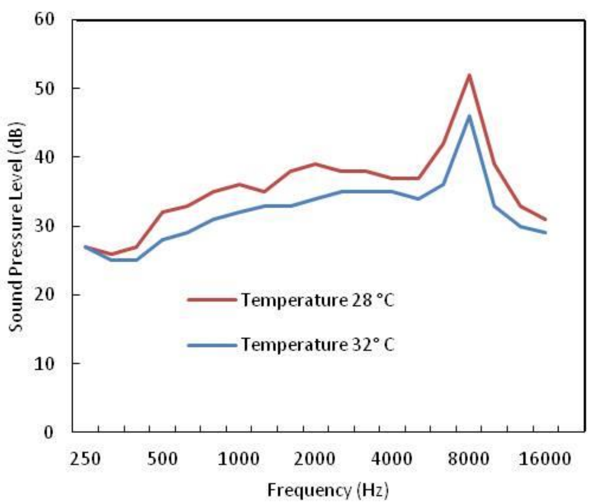


Fig. 16 Examples of background noise levels in the morning (28 °C) and afternoon (32 °C) of the same day

In summary, an increase in temperature caused (1) an increase in atmospheric absorption and increased attenuation of propagating sounds and (2) a decrease in insect activities and a subsequent decrease in the environmental noise level. Obtained data indicate that the former effect had greater influence on detection and recognition of sound sources than the latter. An exception was the car horn sound, which was easier to detect and recognize during warmer weather because of the decrease in environmental noise level.

6.5 Individual Differences

Detection and recognition data obtained in the current study are as distinctive for each listener as for the conditions in which the data were collected. During an outdoor study, and especially over long distances, individual hearing abilities, the confidence of the listener, and the weather effects on the sound spectrum combined with the effects of changing background noise (insects, wind, traffic, etc.) all determine what is heard and how far away it can be identified.

Figures 17–20 contain the graphs of the percentages of correct detection and recognition judgments for each sound by the whole group of participants. The average percentages of detections and recognitions were about 55% and 54%, respectively, for all the sounds and across all distances for all listeners. The corresponding standard deviations were about 12% and 13%, respectively. Having the fewest correct responses, the Joe sound was the most difficult for participants to detect and recognize, while the car horn sound was the easiest, having the most correct responses (see Figs. 17 and 18).

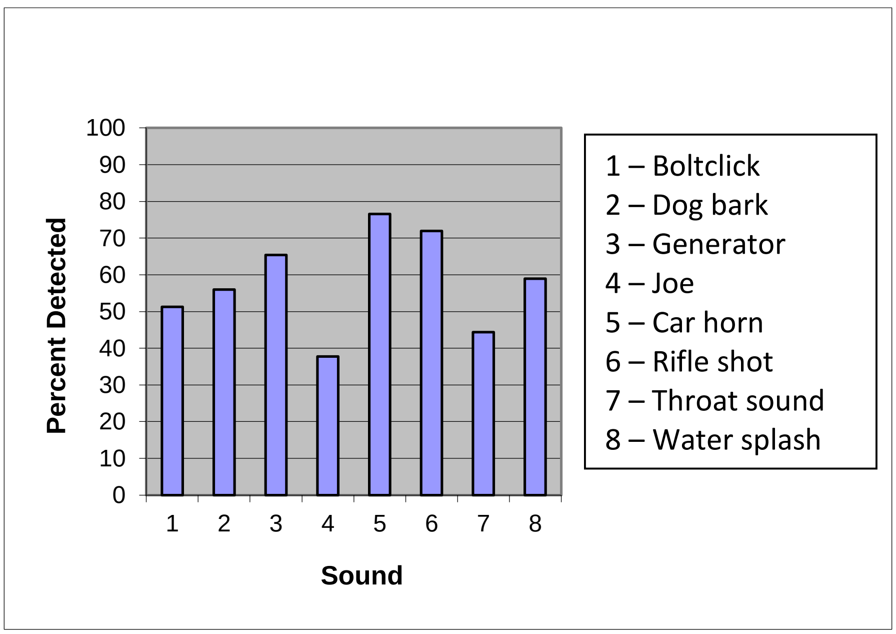


Fig. 17 Average detection percentages of individual sounds for all participants

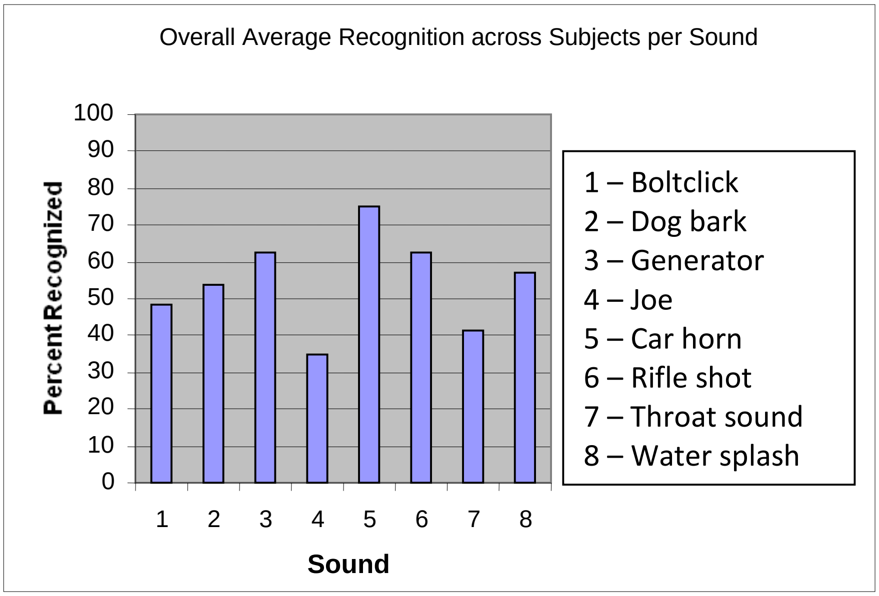


Fig. 18 Average recognition percentages of individual sounds for all participants

Individual performance varied across participants, as shown in Figs. 19 and 20, for detection and recognition, respectively. The overall detection rate among participants varied from 35% to 70% while recognition rate varied from 36% to 71%. For both the detection and recognition tasks, participants 21, 7, and 17 were consistently better than most participants, while participants 4 and 19 were the low performers in both tasks.

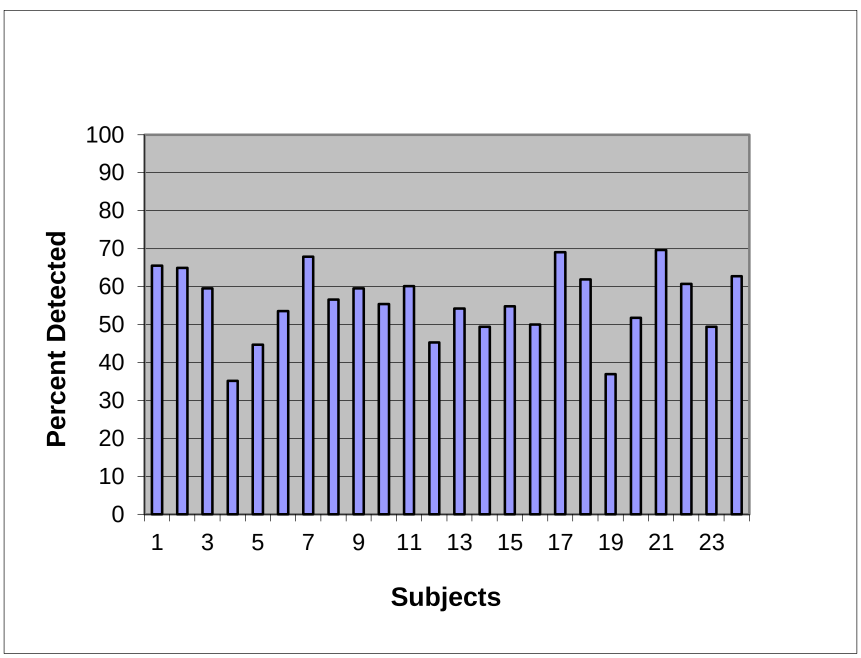


Fig. 19 Average detection percentages for all sounds by individual listeners

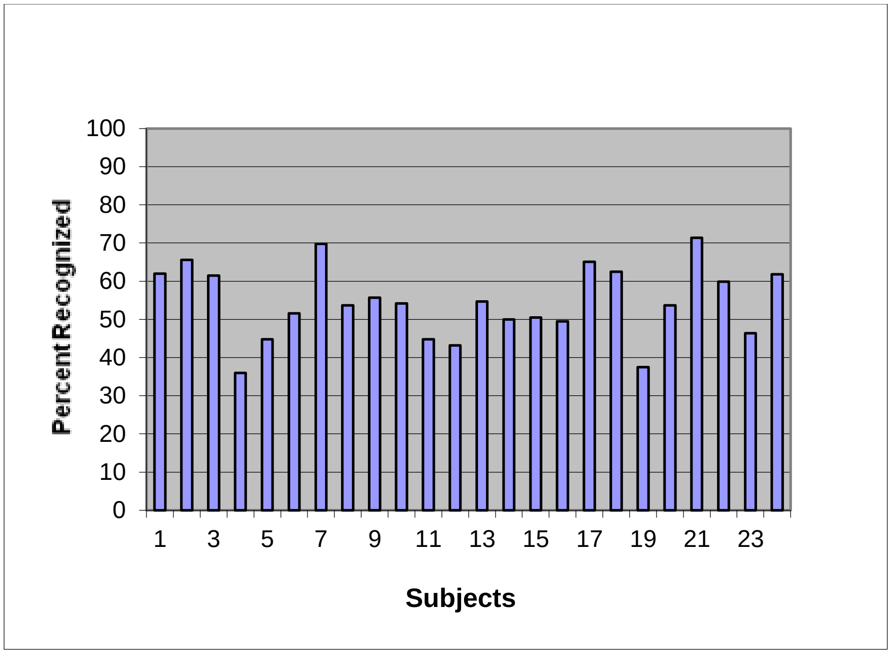


Fig. 20 Average recognition percentages for all sounds by individual listeners

7. Calculated Detectable Spectra

In order to determine what kind of spectra the sounds had when they were detected by the listeners, a simple software program to calculate such spectra was written in-house by one of the authors (Szymon Letowski). The software was an implementation of the sound propagation algorithm shown as Eq. 8 (Salomons 2001). Calculations were made for the average weather conditions, except the wind speed condition that was set to be zero. The model calculated sound spectra at the listener's location generated by the loudspeakers located at distances bracketing the average detection distances reported in this study. The resulting spectra are shown in Fig. 21 together with the spectrum of the average background noise at the listener's location.

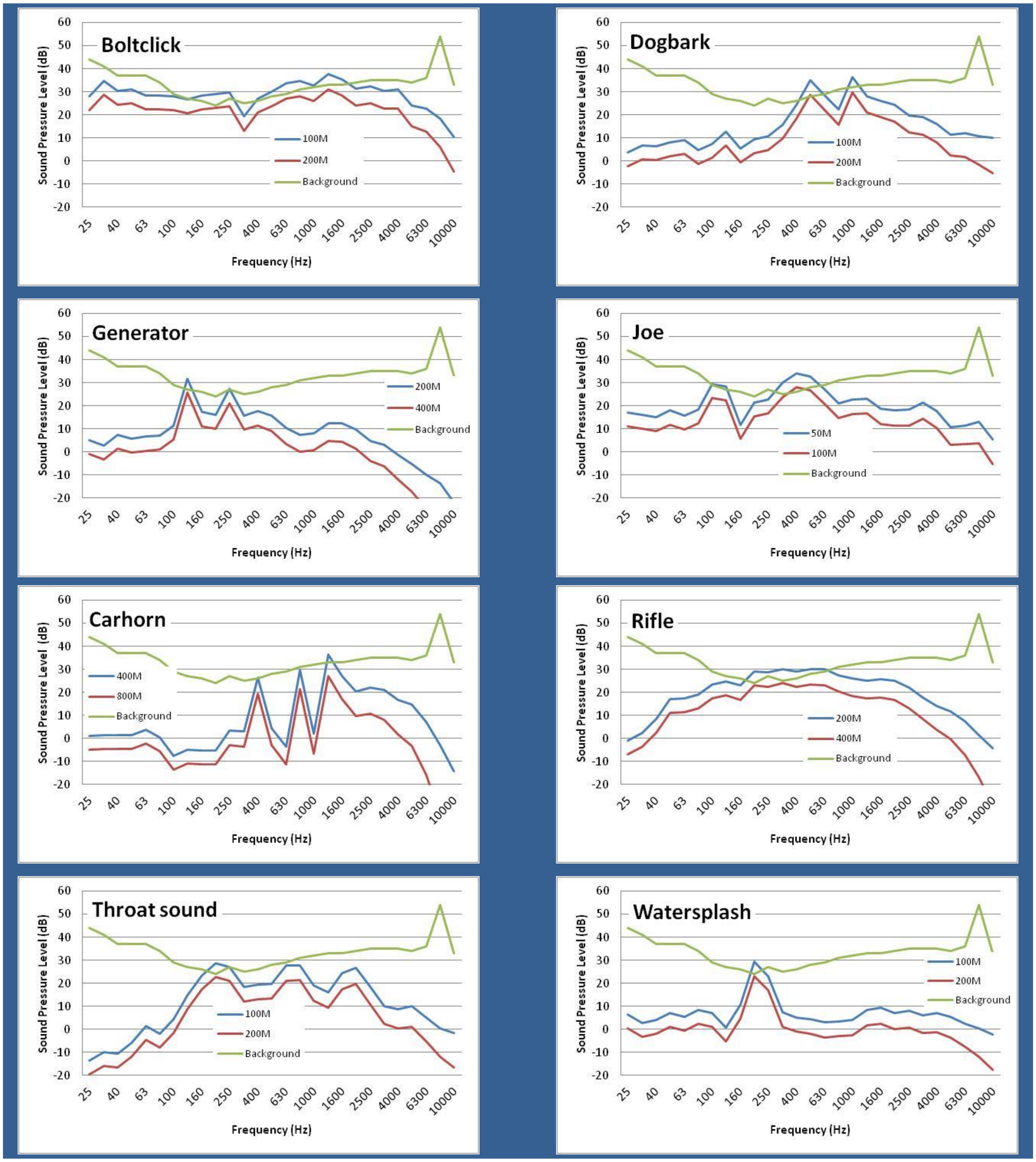


Fig. 21 Average spectra at the listener's location of the individual sounds generated by the loudspeakers bracketing the detection distance for a given sound. The green line shows the average background noise spectrum at the listener's location.

The spectra in Fig. 21 generally show that for sound detection, at least one peak in the spectrum had to exceed the level of the background noise. Based on this assumption more specific sound level and spectrum analyses were conducted using the same software program; the predicted sound detection distances and detection frequencies are shown in Table 18.

Table 18 Detection distances and detection frequencies predicted using sound propagation software model used in this study. The numbers are rounded up to the closest 50-m multiples and one-third-octave frequencies.

Sound	Detection Distance (m)	Frequency (Hz)
Bolt click	150	1250
Dog bark	200	500
Generator	300	125
Joe	100	500
Car horn	600	1250
Rifle	350	315
Throat sound	150	200
Splash	150	200

Taking into consideration the limited features of the applied sound propagation model, the agreement between its predictions and the human data is very good. Some small overpredictions may be noticed for sounds that were detected by their low-frequency content. At these frequencies sound recognition by the listeners was quite difficult; this also affected sound detection. As discussed previously, in this type of experiment sound detection is based to great extent on sound recognition, and detection and recognition perceptual distances were practically identical for all the sounds used in the study.

8. Conclusions

This study has been unique in its scope and in the range of distances to sound sources explored. There are no literature data that the obtained results can be compared against. Therefore, the specific data should not be generalized beyond the conditions explored in the study and should be treated as a first-order approximation of the actual detection and recognition ranges.

Overall, an increase in the distance to the target sound source (which therefore decreases its intensity) decreased participants' accuracy in detecting and recognizing all target sounds. The average detection and recognition ranges of most sounds were approximately 100–200 m. Therefore, it may be hypothesized that this range makes up the soundscape or the range of the basic acoustic environment (and the human safety perimeter) of the listener. This human auditory perception safety perimeter of 200 m is just shorter that the 300-m range that Ehrhart (2009) cites as the range for which current equipment, training, and doctrine are optimized for Soldier lethality.

Within the constraints of the study, the following conclusions and summary based on the obtained data and the investigated weather conditions can be made:

- The detection range for natural sounds used in the study varied from 80 m (Joe) to 640 m (car horn).
- The 3 sounds that were an exception to the average detection and recognition range were car horn, generator, and rifle, which may have been because people are accustomed to hearing them from far away distances.
- Detection range varied considerably across listeners for most of the sounds. The 2 exceptions were Joe and throat clearing sounds for which the detection range was remarkably consistent across listeners. This may be because these are human sounds, and people are not accustomed to hearing them beyond a certain range.
- Sound recognition required similar distance to the sound source as sound detection. This is because once the sound is detected in the natural environment, it is recognized. In general, when a person hears something but does not recognize it and the sound fits the surrounding environment, the sound is considered to be a part of normal environmental variability, and its detection is not registered.
- Detection distances for most sounds were shorter during the hot (except car horn) and dry conditions. This conclusion is limited to specific ranges of temperature and humidity encountered in the study.
- In all cases detection and recognition distances improved (increased) with downwind propagation (as much as twice for bolt click, dog bark, and car horn).
- An increase in air temperature resulted in less insect noise and activity, making detection and recognition distances shorter on hot afternoons.
- Detection distances predicted by in-house-developed software implementing a general sound propagation model were close (with slight over predictions) to that of test participants. This indicates that more precise human predictions of distance may be possible with the addition of wind conditions and listener characteristics to the model.

The 2 main limitations of this study were unstable—although predominantly hot—weather conditions and the relatively small number of participants. Both limitations resulted from the exploratory character of the study intended as a first step in a larger and more systematic exploration of human auditory perception in an open field. The focus of future studies should be on exploring various climatic and environmental (e.g., terrain configuration) conditions, various times of the year, and a more extensive sets of sounds. In addition, the data need to be gathered from various populations of listeners with a sufficient number of people in each to generate meaningful normative data.

9. Notes

1. The inverse-square law applies only to point sound sources and spherical waves propagating in all directions in unbound space. In the case of a line sound source (such as a moving train or busy highway) producing a cylindrical wave, the doubling of distance from the sound source results in only a 3-dB reduction of sound intensity level.

2. Atmospheric refraction also affects propagation of light and other electromagnetic waves, which bend because of the variation in air density, and creates such effects as optical mirages (e.g., fata morgana).

3. Wind is a circular variable and wind data processing should be run using one of the methods of circular statistics (see Fisher [1987] and Letowski and Letowski [2012]).

4. This is an empirical formula predicting the amount of sound attenuation (in decibels) caused by a certain minimal thickness of a belt of trees.

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